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**PREDICTION OF UNDERGROUND NUCLEAR EXPLOSION
EFFECTS IN WAGON WHEEL SANDSTONE**

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Abstract

Project Wagon Wheel is a joint study by Lawrence Radiation Laboratory (LRL) and El Paso Natural Gas Co. (EPNG) to investigate the technical concept of nuclear stimulation of a natural gas reservoir located near Pinedale, Wyoming. This paper presents the results of computer calculations, simulating the explosion effects, based on equation-of-state measurements of core samples taken from EPNG Wagon Wheel No. 1 hole at a depth between 8,000 to 12,000 ft.

The shear failure envelope for Wagon Wheel sandstone is almost identical to that for Hoggar granite. A calculation for Wagon Wheel sandstone for one-kt energy at a depth of 300 m duplicated cavity radius, shear fracture radius, stressed region, peak particle velocity, and peak acceleration data measured from the nuclear experiments conducted in the Hoggar granite by the French. The conclusion drawn from this comparison is that the Hoggar granite chimneys and regions of increased permeability provide a reasonable model to assume for Wagon Wheel.

A single explosive detonated at a depth of 10,000 ft is predicted to produce a

cavity radius of $5.77 W^{1/3}$ (m, kt^{1/3}), with shear fractures extending out to 2.5 cavity radii followed by a stressed region to 5 cavity radii. The expected chimney will have a radius of 1.2 cavity radii and a height of 2.5 cavity radii above the shot point, resulting in an apical void at the top representing about 50% of the cavity volume. Large increase in permeability is expected only within the region of shear fracture.

Chimney height for multiple detonations is expected to be 4 cavity radii based on a rubble porosity of 21%. Explosive spacing for multiple simultaneous detonations varies from a minimum of 5 cavity radii (tangent chimneys) to 7.0 cavity radii based on maximum fracture increase due to shock interaction. Explosive spacing for sequential detonation varied between 7.5 and 12.5 cavity radius based on the similarity between cratering phenomenology (reflecting a shock from the ground surface) and reflecting a shock off the apical void of a previously formed chimney. It is expected that a permeable annular ring will form around the axis between the two explosives to connect the lower chimney with the cavity above.

Introduction

Detonation of a deeply buried nuclear explosive creates a stress discontinuity of tens of megabars which propagates into the surrounding media. This stress discontinuity (shock wave) deposits energy in the rock and is thus attenuated as it propagates radially from the source.

Initially enough energy is deposited to vaporize the rock (approximately 70 tons of rock is vaporized per kiloton of explosive energy); only enough additional energy is deposited from the outgoing shock wave to melt the rock out to about twice the radius of vaporization. Beyond this the rock is fractured until, at large distances from the source, the shock wave has decayed to a point to where it propagates elastically. The cavity (formed by the vaporized region) expands until the pressure in the cavity is in equilibrium with the stresses in the rock. This equilibrium point is defined as the cavity radius R_c . By processes not well understood at the present time, the upper hemisphere of the cavity collapses. Once initiated, the collapse generally continues rapidly until it is terminated by a natural arch or until

the top is supported by the bulked rock. The collapsed region has been described as the chimney because of its usual cylindrical shape, with the axis of symmetry oriented perpendicular to the bedding. The height above the shot point at which collapse terminated is defined as the chimney height. The radius of the chimney may vary between 1 to 1.4 times the cavity radius.

Gas flow calculations¹ have indicated that the most important parameters of the explosive effects to gas stimulation are the chimney height, the chimney radius, and the horizontal extent of increased permeability. The increased permeability may correlate with the degree and type of fracturing in the fracture region.

The purpose of this paper is to predict the cavity radius, chimney height and fracture radius. Also, effects from sequential and simultaneous detonation of several explosives will be estimated. The predictive techniques used (numerical calculations and scaling) require an extensive knowledge of the rock properties.

The Material Properties

Based on the properties of the gas reservoir, the intervals selected for explosion effects prediction were from 9,000 ft to 10,500 ft and from 11,300 ft to 11,800 ft where there were indications of gas in place. A cross section of these intervals showing the general stratigraphy, cored sections, and selected wire line logs is shown in Fig. 1 for the Wagon Wheel

Hole No. 1 located in the NE/4 SE/4 of Section 9, T-30-N, R-108W Sublette County, Wyoming.

Selected core samples were analyzed for their strength and other mechanical properties by LRL² and Tera-Tek Inc.³ The Tera-Tek analysis (performed for EPNG) was limited to analysis of one sandstone sample. The LRL tests were more

Fig. 1. Cross section of intervals selected showing the general stratigraphy cored sections, and selected wire line logs.

extensive and included tests on samples from several locations. It should be noted that almost all tests by LRL and Tera-Tek Inc., were in excellent agreement, as were laboratory measurement of density and compressional velocity with the wire-line logs. Pressure-volume relationship to

40 kbar and the failure envelope are given in UCRL-50963, Ref. 2. Shock Hugoniot⁴ measurements are given in Table 1.

In the static tests it was also noted that in a pressure excursion up to 40 kbar and back to zero there was about 1% irreversible compaction.

Table 1. Results of the Shock Hugoniot Measurement.

	ρ_0	U_s	U_p	σ	V
Wet	2.474	7.44	3.35	617	0.222
Dry	2.422	7.45	3.38	610	0.226
Dry	2.425	7.49	3.37	612	0.227
Wet	2.450	5.55	1.99	271	0.262
Wet	2.440	5.50	2.00	269	0.261
Dry	2.430	5.46	2.01	267	0.260
Dry	2.430	5.53	2.00	269	0.263
Wet	2.438	5.20	1.34	170	0.304
Wet	2.451	5.16	1.34	170	0.302
Dry	2.422	5.16	1.35	169	0.305
Dry	2.398	5.17	1.34	167	0.309

ρ_0 = bulk density in gm/cm³

U_s = shock velocity m/msec

U_p = particle velocity m/msec

σ = principal stress kbar

V = specific volume cm³/gm

The driving pressure for the calculations was the cavity pressure-volume curve shown in Fig. 2. This curve is based on the SiO₂ + 1% H₂O gas equation-of-state and adiabatic expansion relationship developed at LRL.⁵

The calculation is started at the time when the vaporized cavity is formed so that the computer does not need to consider whether hydrodynamic heating vaporizes any more rock. The vaporization radius is calculated from the expression $R_v = CW^{1/3}$ (R_v is in m, W is in kt) where $C = 1.9$ for sandstone of density 2.45 gm/cm³. The initial pressure of the cavity gas at the end of the vaporization phase is 1.55 Mb.

Figure 3 shows the pressure-volume relationship of the rock used as an aver-

Fig. 2. Cavity gas pressure - volume relationship.

Fig. 3. Pressure - volume relationship for Wagon Wheel rock between depths of 9,000 ft to 12,000 ft.

age between the depths of 9,000 ft and 12,000 ft. This is based upon both the Hugoniot data and the measured compressibility of the rock. An average Poisson's

ratio of 0.2 was selected based on the one-dimensional strain tests.

Figure 4 shows the failure criteria used as developed from the shear strength measurements in the form of K_S versus $\bar{P}$ as defined below

$$\bar{P} = (\sigma_1 + \sigma_3)/2$$

$$K_S = |\sigma_1 - \sigma_3|/2$$

where σ_1 and σ_3 are the minimum and maximum principal stress respectively. The shear strength curve was extrapolated from 10 kbar of shear strength to 15 kbar and then assumed constant.

Fig. 4. Shear strength criteria.

Analysis of Previous Nuclear Experiments

Numerical codes developed by Cherry and Peterson⁶ in conjunction with a compatible material-properties-measurement program developed by Stephens, Schock and Heard^{7,8,9} have led to a reliable predictive capability for phenomena associated with shock wave propagation. Calculations of cavity radius, peak shock stress particle velocity, and fracture radius associated with chimney height have been confirmed by various experiments. A model or suitable experiment is still required to predict the degree of fracture, the chimney configuration and the permeability increases in the fractured and stressed rock.

The first step in selecting appropriate nuclear experiments is to compare the materials properties measured for Wagon Wheel with those of other experiments. On the basis of porosity and water content, all experiments in tuff and alluvium and their associated scal-

ing laws can be eliminated from consideration. Eliminating others for a variety of reasons leaves experiments in Nevada Test Site (NTS) granite, Gasbuggy and the Hoggar granite.¹⁰ Table 2 compares the material equation-of-state (EOS) parameters with Wagon Wheel parameters.

Figure 5 compares the strength curves measured for these media with Wagon Wheel sandstone.

Cherry and Peterson in Ref. 6 present a fairly complete numerical analysis of Hardhat (5 kt in NTS granite) and Gasbuggy (26 ± 3 in a gas bearing sandstone) verified by experimental measurements. This analysis indicated two types of fracturing which proceed to different radii from the shot point. The first is the limit-of-shear fracture where the rock no longer fails on compressive loading, and the second is the maximum limit fracture where the rock has failed in extension. The fractures are

Table 2. Material EOS parameters compared with Wagon Wheel parameters.

Medium	ρ_0	V_p	σ	H_2O	ϕ	Kmax
NTS granite	2.67	5.3	0.28	2	1.4	2.0/7.5*
P.C. ⁺ sandstone	2.5	3.5	0.3	2.7	8.0*	3.0
Lewis ⁺ shale	2.6	3.5	0.3	1.9	—	2.0
Hoggar granite	2.63	5.5	0.3	0.3	0.3	unk
Wagon Wheel sandstone	2.45	4.5	0.2 [‡]	2.0	8.0*	15.0

* Hugoniot elastic limit for NTS granite is 7.5 kbar.

ρ_0 = initial density gm/cc

V_p = compressional velocity m/msec

σ = Poisson's ratio

H_2O = water content by weight %

ϕ = porosity in %

Kmax = maximum shear strength (kbar)

* = 8% porosity and 60% saturation

+ = Gasbuggy

‡ = average of 0.14 loading and 0.3 unloading

Fig. 5. Media strength curves compared to Wagon Wheel.

interconnecting between the cavity and the shear fracture radius; this seems to be the boundary of chimney growth. In the second fracture zone, only radial fractures are created.

In terms of strength, fractured wet NTS granite is similar to Gasbuggy sandstone, whereas dry solid NTS and Hoggar¹⁰ granite is similar to Wagon Wheel sandstone. In granite, the quartz grains are closely packed and allow little rotation or translation of the quartz grains so that the granite deforms elastically until brittle failure occurs.¹¹ Even at shear stresses one-half of the shear strength of granite, microfracturing occurs, resulting in dilatancy which may increase permeability.

The sandstones, however, behave quite differently under stress loading. The quartz grains are surrounded by a relatively ductile matrix, allowing them to undergo considerable translation and rotation. This cataclastic flow and microfracturing results in the observed mechanical ductile behavior of the test samples.¹²

The difference in the ultimate strength between Gasbuggy and Wagon Wheel Rock is attributed to the stronger matrix components of the sandstone as well as the fact that Wagon Wheel sandstone has more than twice the grain-to-grain contacts per quartz grain as Gasbuggy sandstone.¹²

The Wagon Wheel sandstone exhibits dilatancy only near the failure envelope and actually compacts due to shear at lower stress levels.² The Wagon Wheel sandstone under one-dimensional triaxial shear tests (representing the shock loading path at low strain rates) will not develop the stress conditions required for failure. Poisson's ratio under these tests varies from an initial 0.13 at 1 kbar to about 0.3 at 4 kbar of axial stress.² However, at the higher strain rates occurring under shock conditions, the Wagon Wheel sandstone is expected to show considerably less ductile behavior. The shear stress should increase with mean stress with an average Poisson's ratio of 0.2, intersecting the failure envelope at about 8 kbar of shear stress. This assumption on the effect of strain rate is supported by the agreement between the calculated⁶ and experimentally verified¹ permeability increase with distance for Gasbuggy. The sudden loss of the high distortional energy at these stress levels results in extensive fracturing. On this basis, the ultimate shear strength be-

comes the dominant equation-of-state parameter.

The only nuclear experiments in a medium with shear strength similar to Wagon Wheel are the French detonations in Hoggar granite.

The French experiments in the Hoggar granite were at low to moderate yields at depths between 200 to 400 meters.¹³ The scaling laws developed for the media are given below.

- Cavity radius, defined as the interface between the melt and the solid rock.

$$R_c = 7.3 W^{1/3}$$

and also

$$R_c = \frac{52 W^{1/3}}{(\rho gh + C_s)^{1/3} \gamma}$$

where

$$\gamma = 1.03$$

ρgh = overburden pressure in bars

C_s = strength term in bars

$$120 < C_s < 320$$

R_c = Cavity radius in m

W = Explosive yield in kt

- Radius of crushed zone - between the cavity and this radius the rock has been pulverized.

$$R_b = 10 W^{1/3} \text{ (m, kt}^{1/3}\text{)}$$

also

$$1.3 R_c < R_b < 1.8 R_c$$

- Radius of fracture - this radius is also the limit to which the French assumed the chimney will grow and, if consistent with SOC calculations, is the maximum extent of shear fracture.

$$R_f = 26 W^{1/3} \text{ (m, kt}^{1/3}\text{)}$$

- Radius of stress zone - this zone is defined by the drill core fracturing

in parallel disks, indicating a highly stressed region is being relieved.

Also, some preshot or shock induced fractures are encountered.

$$R_R = 35 W^{1/3} \text{ (m, kt}^{1/3}\text{)}$$

In order to compare the Wagon Wheel rock with the Hoggar granite, a SOC calculation, using the Wagon Wheel EOS, was made for a yield of 1 kt with an overburden pressure of 70 bars representing the initial conditions of the Hoggar data. The results are presented in Fig. 3.

Figure 6 shows the cavity radius, limit of compressive failure, fracture initiation and the shock front as a function of time.

The double line at the shock front indicates the width of the shock from maximum acceleration to peak pressure.

Fig. 6. Cavity radius, limit of compressive failure, fracture initiation, and shock front as a function of time for 1 kt.

Table 3. Calculated results compared with Hoggar granite experience.

Radius (m)	Calculation	Hoggar granite
R_c	7.2	7.3
R_b	10.5 - 12.0	10.0 - 14.0
R_f	26.0	26.0
R_R	38 - 48	35

Table 4. Radius of crush zone determined by comparing crack number for each zone.

Zone number	Crack number		Radial distance (m)
	T = 25 msec	T = 50 msec	
970	1	3	12.016
971	2	5	11.744
972	2	4	11.474
973	2	4	11.210
974	2	4	10.949
975	2	4	10.694
976	3	6	10.444
977	3	6	10.200
978	3	6	9.361
979	3	7	9.729
980	4	8	9.504
981	4	8	9.287
982	4	9	9.077
983	5	10	8.876
984	6	11	8.683
985	8	15	8.500
986	12	19	8.328
987	16	23	8.165
988	18	26	8.013
989	25	33	7.873
990	32	40	7.743
991	49	58	7.520
992	56	64	7.343
993	58	67	7.210
994	Melt	Melt	7.060
995	Gas	Gas	6.123

Fig. 7. Crack number as a function of distance.

Fig. 8. Particle velocity at shock front vs scaled range comparison with Hoggar granite.

Table 3 compares the calculational results with the Hoggar granite experience.

The radius of the crushed zone was determined by comparing the increase in the crack number for each zone between 25 msec and 50 msec as shown in Table 4. Radial distance is given at the time of 50 msec. The assumption is that the crushed zone was formed by continued re-fracture over a period of time. This is further emphasized in Fig. 7 which shows the crack number as a function of distance.

Figure 8 compares the measured peak particle velocity¹⁴ at the shock front for Hoggar granite with the SOC calculation using the Wagon Wheel EOS. Figure 9 is a comparison of the scaled acceleration.

Fig. 9. Scaled acceleration at shock front vs scaled range comparison with Hoggar granite.

The solid curve in Fig. 9 is a least square fit to the data and also the maximum acceleration at the shock front as calculated by SOC. The dashed curve is the SOC peak velocity divided by the rise time to give a

minimum particle acceleration. Thus, on the basis of all available data, it seems that the experiments in Hoggar granite will provide an excellent model for Wagon Wheel.

Numerical Calculations for Wagon Wheel at Depth

Using a numerical model of stress wave propagation (SOC)⁶ with the material properties just presented, the stress-induced effects on the rock mass were determined at various yields and overburden pressures for Wagon Wheel. Table 5 compares some of the basic results from these calculations. Calculations 1, 4, and 5 are for depths of 9,600 ft. Calculations 2, 3, and 6 are at the overburden pressures of Gasbuggy, Rulison, and French experiments, respectively.

Figures 10 and 11 show the positions of the shock front, initiation of fracture, and cavity radius with respect to time for calculations 4 and 5, respectively. The separation between shear failure on shock loading and extension failure on unloading is clearly defined as the separation of the fracture initiation (limit of fracture) curve from the shock front.

Figures 12, 13 and 14 show the radial stress, shear stress, and velocity, respectively, as a function of distance at the

Table 5. Results of stress-induced effects on rock mass at various yields and overburden pressures.

Calc	W (kt)	P _{ove} (kbar)	R _v (m)	R _c (m)	P _c (kbar)	R _{sf} (m)	R (mxf) (m)
1	20	0.7	5.15	15.25	1.02	40	78
2	30	0.31	5.89	19.3	0.7	54	118
3	40	0.43	6.486	20.7	0.82	55	125
4	40	0.7	6.486	19.5	1.02	50	101
5	100	0.7	8.80	26.6	1.02	70	139
6	1.0	0.07	1.896	7.2	0.47	26	48

where

W = yield in kt
P_{ove} = overburden pressure
R_v = radius of vaporization
R_c = final cavity radius
P_c = final cavity pressure
R_{sf} = shear fracture radius
Rmxf = maximum possible radius of fracture

Fig. 10. Radial distance vs time at yield of 40 kt.

Fig. 11. Radial distance vs time at yield of 100 kt.

Fig. 12. Radial stress vs radius at 120 ms at 10,000 ft d.o.b.

Fig. 13. Particle velocity vs radius at 120 ms at 10,000 ft d.o.b.

time the cavity is in quasi-equilibrium for calculation no. 4. Between the cavity and the limit of shear fracture radius, the radial stress increases with distance and is the minimum principal stress (i.e., $K_{r\theta} = -(\sigma_{\theta} - \sigma_r)/2$ is negative), and thus, this is a region where tangential fractures predominate.

Fig. 14. Shear stress vs radius at 120 ms at 10,000 ft d.o.b.

Between the limit of shear fracture and the maximum fracture radius, $K_{r\theta}$ is positive, indicating that the fractures should be radial in this region. Outside the maximum fracture radius, the rock has been stressed but remains essentially unfractured.

Figure 15 shows the crack number for calculation 4 and 5 as a function of distance horizontally from the shot point. The crack number is the number of times the failure envelope has been exceeded. Corresponding limits of fracture radii are shown, indicating the relative degree of fracture in these zones.

Fig. 15. Crack number for calculations 4 and 5 as a function of distance horizontally from the shot point.

Scaling Laws for Wagon Wheel

Based on the preceding calculations, the scaling curves for Wagon Wheel were developed as shown in Figs. 16 and 17. Using an adiabatic expansion formulation for the cavity gas as did the French,^{15,16} the equation for the cavity radius is

$$R_c = \frac{\alpha P_v^{1/3\gamma} R_v}{P_c^{1/3\gamma}}$$

where

- * $\alpha = 1.05$ to account for the melt
- $P_v = 1.550$ Mbar vaporization pressure
- $\gamma = 2.3$ $P > 1$ kbar
- $\gamma = 1.14$ $P < 1$ kbar } see Fig. 2
- $R_v = 1.9 W^{1/3}$ radius of vaporization
- $P_c =$ cavity pressure at equilibrium in kbar

*Note: The α used by French is based on shot room void not being vaporized.

Fig. 16. Cavity radius vs overburden.

Fig. 17. Ratio of fracture radii to cavity radius vs overburden.

Doing the arithmetic results in

$$R_c = \frac{5.77 W^{1/3}}{P_c^{1/3\gamma}}$$

where the distance is expressed in meters and the yield (W) in kilotons.

The cavity pressure is approximately 0.4 kbar greater than the overburden which is the mean strength term for the rock (Table 5), and for pressures less than 1.4 kbar, the use of a $\gamma = 1.14$ results in errors of less than 5%. Substituting, we have

$$R_c = \frac{5.77 W^{1/3}}{(\rho gh + 0.4)^{1/3.42}}$$

The difference between this equation and that developed by the French for Hoggar granite is basically in the γ assumed for the cavity gas and a slightly smaller strength term. Figure 16 shows the above equation plotted for 4 yields as a function of overburden pressure.

Figure 17 shows the ratio of the various fracture radii, as determined by the

Fig. 18. Wagon Wheel shock stresses vs scaled range.

Fig. 19. Peak particle velocity vs scaled range.

SOC calculation, to the cavity radius. The radius of the crushed zone is independent of the overburden pressure, and thus the ratio increases as the cavity radius decreases with depth. The shear fracture radius and radial fracture radius are strongly dependent on the overburden pressure, requiring higher shock stresses to fracture.

Figure 18 shows the peak overpressure at the shock front as a function of scaled distance where P_{ove} is the overburden pressure. Figure 19 shows the peak particle velocity as a function of scaled distance. Figure 20 shows the peak scaled acceleration in gravitational units as a function of scaled distance.

Fig. 20. Scaled acceleration vs scaled range.

Chimney Configuration

Chimneys observed in Hoggar granite¹⁷ are of two types. One is asymmetric perpendicular to the bedding with $R_{ch} = R_c$. The other is oval with $R_{ch} \sim 1.4 R_c$ about $2 R_c$ above the explosion point. Both types do not extend beyond the shear fracture radius. United States experience is similar.

The rock from the site of Gasbuggy has a higher ductile matrix content than that from Wagon Wheel; therefore, it is likely that a chimney will form at Wagon Wheel. The chimney is expected to flare

outward with a slope of about 5° . This is intermediate between the two cases in Hoggar granite and is somewhat greater than the U.S. experience. It is based on expected particle size¹⁸ and experience in rock flow in ore passes.^{19,20}

Figure 21 shows the expected chimney and associated fracture pattern for a single explosive at 10,000 ft depth. The crushed or pulverized region extends to $1.6 R_c$, the shear fracture to $2.5 R_c$ and the maximum radial fracture to $5.1 R_c$. The chimney radius measures $1.2 R_c$ at

Fig. 21. Chimney configuration and fracture pattern for Wagon Wheel.

an elevation of $2.0 R_c$ above the shot point. The total chimney height is $2.5 R_c$. Using a porosity of 0.21 for the rubble gives an apical void of 0.5 cavity volumes, and a void height of $0.4 R_c$. The maximum chimney height based on a porosity of 0.21 would be $4 R_c$ if the chimney were allowed to grow beyond the fracture radius.

Based on permeability measurements in the Hoggar experiments¹⁰ and gas flow test analysis of Gasbuggy,¹ permeability is expected to be greatly enhanced within the shear fracture region. In the radial fracture region, permeability is expected to be slightly higher than the initial value, but beyond this no increase is expected as dilatancy arguments are not applicable. Static equilibrium of the rock around the chimney requires that the radial stress adjust from a maximum to a minimum principal stress. This may result in tangential fractures leading to an increase in permeability. This effect would be greatest above the chimney and negligible below.

Multiple Explosive Spacing and Effects

At present, there are no previous experiments on which to judge or estimate the effects from multiple explosions in the same well bore. Also, no two dimensional calculations have been possible within the time limit of this report. Therefore, the explosive spacing and effects are based on an extrapolation of the one-dimensional analysis.

There are two approaches to the timing of the detonations of the explosives, simultaneous and sequential. Simultaneous as used here means that the explosives are

fired within a millisecond of each other. Sequential firing means time delays between detonations greater than several minutes and may be timed until after collapse of the previous chimney.

For Hoggar granite a scaling law on the time of collapse has been developed.²¹

$$t(\text{min}) = 1.25 R_c - 375$$

where R_c is the cavity radius in meters

for 40 kt, $t = 21$ min
for 100 kt, $t = 29$ min.

SIMULTANEOUS EXPLOSIVE EFFECTS

The shock waves from the two explosives will meet at the midpoint between them. The stress conditions on the rock will be almost identical to a laboratory triaxial test resulting in a fracture pattern parallel to the emplacement hole. As the shocks pass each other, the particle velocity will be reversed and horizontal fractures develop and separate. As the shock from one explosive reaches the expanding cavity of another, the growth of the cavity along the shot line is temporarily reversed, but normal to the shot line the growth is increased. This should result in elliptical cavities rather than spherical cavities. Rarefaction of the shock off the cavity should be nonexistent in terms of releasing the stress as relatively high pressures will be maintained throughout the entire region between the explosives. At reasonable spacing the cavity should attain 90% or more of the single explosive volume at the time the shock reaches the cavity. At this time there will be a cylindrical high pressure region between the cavities with pressures 2 to 3 times the cavity pressure. This cylindrical pressure will drive the rock radially away from the shot line and vertically into the cavities. The shock interaction effects just described and the degree and the extent horizontal fractures at the midpoint are dependent on the yield and the spacing of the explosives.

The shear fracture radius for a single explosive at 10,000 ft is calculated to be $2.5 R_c$ where R_c is the cavity radius. Therefore, at a spacing of $5 R_c$ the shear fracture regions will be tangent. From Fig. 18 the stress versus distance for fracturing can be estimated, assuming

converging shock stresses will be additive. On this basis, the maximum explosive spacing which will leave continuously shear fractured rock between detonation points may be estimated to be $7 R_c$.

Figure 22 shows the ratio of height stimulated to the cavity radius as a function of the number of explosives and spacing.

SEQUENTIAL EXPLOSIVE EFFECTS

Sequential firing of explosives arranged in a vertical array allows the use of larger individual yields with less total yield to reduce the possibility of seismic damage.

When the first explosive is detonated, a chimney, shear fracture and stressed region is formed as shown in Fig. 21. The rock in the stressed region above the chimney is in an unstable stress state and in the process of readjustment due to formation of the chimney. Because of this stressed condition, the effective shear strength of the rock is reduced.

The second explosive, detonated some distance above the first chimney, propagates a shock wave which refractures the prestressed region and reflects off the existing chimney as a tensile wave. Figure 23 shows the relative effect on the particle velocity of the shock and tensile waves midway between the second explosive and the lower chimney top. This velocity is also compared with the velocity profile of a particle in the horizontal plane of the second explosive. The particle velocity in location 1 (Fig. 23) increases rapidly under shock loading, then decays due to the high shear stresses. The reflected tensile wave from the chimney increases the velocity again as it passes, spalling

Fig. 22. Ratio of height stimulated to cavity radius as function of the number of explosions and spacing.

the rock. The cavity created by the second explosion is in a quasi-equilibrium state at the time the reflected tensile wave reaches it. The cavity pressure then drives the rock below the cavity formed by the second detonation down into the lower chimney void, shearing along the cylindrical zone which has previously been weakened by the tensile wave. The logical analysis of the phenomena shock, spall, and gas acceleration is based on analysis of cratering experiments.²² The relative magnitude of each effect depends on yield of the second explosive and on the distance between this explosive and the free surface of the existing chimney.

Overburden pressures are minimal in cratering experiments, resulting in large

Fig. 23. Velocity profile between multiples fired sequentially.

spall effects and gas drive pressures of as much as 200 bars. For overburden pressures at 10,000 ft depth, velocity enhancement from spall would be severely reduced and confined to a cylindrical region

Fig. 24. Spall effects as function of explosive spacing.

about the axis connecting the two explosives. However, cavity pressures will equalize at about 1 kbar, providing considerable enhancement of the gas acceleration phase.

Peak surface velocity measurements made on cratering experiments indicate that surface velocities of 34 m/sec or greater are sufficient to form craters, and velocities of 24 m/sec are sufficient to form retards.²³ These velocities correspond to scaled distances between the explosive and the free surface of $51 \text{ m/W}^{1/3}$ and $61 \text{ m/W}^{1/3}$, respectively ($\text{m/kt}^{1/3}$).

Figure 24 shows the peak spall velocity and radial overpressure at the upper surface of the chimney resulting from the first detonation as a function of the initial spacing of the explosives, assuming a chimney height of $2.5 R_c$.

On this basis, for Wagon Wheel sandstone, explosive spacing up to $12.5 R_c$ is expected to produce a continuous chimney. However, it should be noted here that there is a possibility that the assumptions regarding the chimney produced by the first detonation may not be confirmed. That is, upon the detonation of the first explosion an appreciably shorter chimney may be formed than has been previously assumed, or the chimney which does form may be completely filled with debris, and display no apical void. In either of these cases, the effective reflection of the shock wave from the first chimney toward the region around the second explosive will be significantly less than for the optimum first chimney configuration.

This, then argues for a somewhat closer spacing between the two explosives to present a higher probability of complete collapse in the inter-explosive region. Thus, it is recommended that the explosive spacing be maintained between $7.5 R_c$ and $10 R_c$ for Wagon Wheel.

Summary

Laboratory tests and studies of the Wagon Wheel sandstone developed the behavior characteristics of the rock under stress loading. The similarity of the shear strength between Wagon Wheel sandstone and Hoggar granite and the resulting nu-

merical calculation of the shock induced effects measured on the experiments in Hoggar granite, provided a degree of confidence in the calculations for Wagon Wheel at depth. It also provided a model for chimney configuration. At a depth of

10,000 ft, the chimney radius should be $1.2 R_c$ and the height of the chimney should be $2.5 R_c$ above the shot point with an apical void at the top. A radius of increased permeability extends to $2.5 R_c$ from the shot point.

With the above model and confidence in the equation-of-state measurements

and the calculations based on those measurements, it was possible to deduce the interaction processes for multiple explosives in the same well bore.

This resulted in a spacing of the explosives of $5 R_c$ to $7 R_c$ for simultaneous and $7.5 R_c$ to $12.5 R_c$ for sequential detonation.

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