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EFFECT OF WATER CONTENT, YIELD, MEDIUM,
AND DEPTH OF BURST ON CAVITY RADII

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February 21, 1967

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EFFECT OF WATER CONTENT, YIELD, MEDIUM, AND DEPTH OF BURST ON CAVITY RADII

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February 21, 1967

ABSTRACT

Cavities produced by nuclear explosions can be accurately described provided that water content, medium density, and explosive energy are known. The equation

$$R_C = 100 \left[\frac{(\bar{\gamma} - 1) P_v W}{(\rho h)^{\frac{1}{\gamma} + 1}} \right]^{1/3}$$

describes results of 46 nuclear detonations in tuff, alluvium, salt and granite to the accuracy with which the cavity radius and other variables can be determined. The adiabatic expansion coefficient, $\bar{\gamma}$, depends strongly on the water content of the medium. There is no indication that cavity size depends on the strength of the rock medium in which the explosion is detonated.

INTRODUCTION

In 1959, Nuckolls,¹ after calculating the effects of the Rainier nuclear explosion, noted that the cavity could be explained by simply assuming the vaporized rock expanded until the pressure was in equilibrium with the overburden pressure. The equations for this explanation are as follows:

$$P_v V_v^{\frac{1}{\gamma}} = P_c V_c^{\frac{1}{\gamma}} \quad (1)$$

$$P_v V_v = (\bar{\gamma} - 1)E, \quad (2)$$

where P_v and P_c are the initial and final rock vapor pressures, V_v and V_c are the vapor volumes before and after expansion, $\frac{1}{\gamma}$ the adiabatic expansion coefficient, and $(\bar{\gamma} - 1)$ a proportionality constant relating the energy, E , to the PV for the rock vapor (an imperfect gas).

Nuckolls went on to write:

$$P_c = \rho gh, \quad (3)$$

where ρ is the average overburden density, g the acceleration of gravity, and h the depth of burst. By combining Eqs. (1), (2), and (3), he obtained

$$V_c = \frac{(\bar{\gamma} - 1)P_v^{\frac{1}{\gamma} - 1} W}{(\rho gh)^{\frac{1}{\gamma}}} \quad (4)$$

where W , the explosive energy in kilotons, was substituted for the energy, E .

In terms of cavity radius, R_c , Eq. (4) is

$$R_c = \left[\frac{3(\bar{\gamma} - 1)P_v^{\frac{1}{\gamma} - 1} W}{4\pi(\rho gh)^{\frac{1}{\gamma}}} \right]^{1/3} \quad (5)$$

¹Personal communication from J. Nuckolls (LRL) to G. H. Higgins (LRL).

For a single medium, P_v and $\bar{\gamma}$ are fixed, and by assuming $\gamma^+ = 4/3$, Eq. (5) reduces to

$$R_c = C \frac{W^{1/3}}{(\rho h)^{1/4}}, \quad (6)$$

where

$$C = \left[\frac{3(\bar{\gamma} - 1)P_v \frac{1}{\gamma^+} - 1}{4\pi g \frac{1}{\gamma^+}} \right]^{1/3} \quad (7)$$

This equation was tested against a large number of nuclear explosions (Boardman, Rabb, and McArthur, 1963).² The constant, C, was derived from observed cavity radii, yields, and depths of burst. The values of C are summarized in Table I. The units used in obtaining C were ρ in g/cm³, h and R_c in meters, and W in kilotons.

Table I. The values of the cavity proportionality constant.

Medium	Derived C
Alluvium	86.6
Granodiorite	79.6
Salt	85.7
Tuff	104.6

C as defined in Eq. (7) is dependent on material since $\bar{\gamma}$, P_v , and γ^+ are all variable from medium to medium. As a result of recently published work (Butkovich, 1967),³ it is possible to evaluate each of these parameters and to study the equation for cavity radius in the following form:

$$R_c = C \frac{W^{1/3}}{(\rho h)^\alpha}, \text{ where } \alpha = \frac{1}{3\gamma^+}, \text{ and} \quad (8)$$

$$\text{the constant } B = \left[(\bar{\gamma} - 1)P_v \frac{1}{\gamma^+} - 1 \right]^{1/3}, \quad (9)$$

and C is as defined in Eq. (7). The information in the following section was summarized from Butkovich's report.

²Boardman, C. R., et al, Characteristic Effects of Contained Nuclear Explosions for Evaluation of Mining Applications, Rpt. UCRL-7350, LRL, Livermore, Calif., May 1963.

³Butkovich, T. R., The Gas Equation of State of Natural Materials, Rpt. UCRL-14729, LRL, Livermore, Calif., Feb. 1967.

DETERMINATION OF THE ADIABATIC EXPANSION COEFFICIENT, γ^+

The medium property which most affects cavity radius is γ^+ . For materials for which data exists γ^+ is the slope of the adiabatic expansion curve for gases (Eq. 1) when log pressure is plotted against log of density or specific volumes.

The first problem with the nuclear explosion cavity is determining which gases are present. It is obvious that when energy density is very high (the first microsecond after the explosion), the materials surrounding the explosive are ionized to nuclei and electrons. Under these conditions and until the temperature drops below about 5 eV, materials are treated according to the statistical models. Below 5 eV, the various nuclei recombine and interact sufficiently that they must be treated species by species. Each molecular species is treated as a perfect gas and partitions between ions, atoms, and molecules are made consistent with thermochemical data.

Almost every real rock vapor contains a number of species so large that a detailed treatment is very cumbersome; therefore, a simplifying approximation was introduced: First, it was observed that crude pressure-volume calculations for Na_2O , CaO , SiO_2 and FeO were quite similar over the region of temperature from a few electron volts to about 0.1 eV — that is, all these materials had similar values of γ^+ . Second, it is a fact that all silicate rocks are preponderantly SiO_2 . The only material of common occurrence which displays a different expansion coefficient is H_2O . Therefore, the approximation selected is that all silicate rocks are comprised of SiO_2 and H_2O at the observed density. This is known as the simple silicate approximation. For densities of vapor less than about 0.2 g/cm^3 , the γ^+ for SiO_2 is about 1.02. For the range of temperature covered by this range of density for SiO_2 gas, the γ^+ for H_2O is about 1.40. Figure 1 is a construction of α , which is $1/3\gamma^+$, versus water content based on these Fig. 1 numbers; no second order molecular interaction is assumed.

Forty-six nuclear events for which data were available were analyzed, and an apparent value of C derived with the exponent on the denominator in Eq. (6) changed from $1/4$ to $1/3\gamma^+$. Results are summarized in Table II and given in detail in the Appendix.

Fig. 1. The adiabatic expansion coefficient, α , plotted as a function of wt % of water in silicate rocks. α is defined as $\frac{1}{3\gamma}$.

Table II. Values of the cavity proportionality content corrected for the medium water content.

Mediums	Approximation	α	ρ	No. events	C	Standard deviation, σ
Granite	SiO ₂ + 1% H ₂ O	0.324	2.7	2	103	*
Tuff	SiO ₂ + 15% H ₂ O	0.292	1.9	11	97	±6
Alluvium	SiO ₂ + 12% H ₂ O	0.296	1.9	30	89.0	±8.1
Salt	None	0.311	2.3	2	96	*
Dolomite	None	0.329	2.3	1	89	*

*No. of events too small for determination of σ .

The maximum difference in C between the media was reduced from 25% to somewhat under 15% by this treatment. Each medium was treated as if there were no place to place water content variation. This assumption is known to be invalid, but credible measurements do not exist at the appropriate locations, so better estimates are not possible. An exception is the Gnome and Salmon events, where the water content was measured (Gnome 4%** and Salmon about 0%). These values were used in the calculations.

** A value of 1.5% is also quoted in Rpt. PNE-107F.⁴

⁴Rawson, D., et al, Project GNOME: The Environment Created by a Nuclear Explosion in Salt, PNE-107F, LRL, Livermore, Calif., Apr. 20, 1965.

DETERMINATION OF P_v

As the shock wave proceeds outward from the center of detonation, it leaves enough internal energy to vaporize the rock close to the detonation point because of the irreversible nature of the shock compression. However, both because the energy is being removed from the shock and because the shock is spherically diverging, the energy drops below that necessary to completely vaporize the rock at some radius. This pressure, that is just sufficient to cause all the rock to vaporize after decompression, is called P_v . The corresponding radius is called R_v . P_v and R_v were determined by using the SOC plastic-elastic hydrodynamic code calculation (Cherry, 1966).⁵ Results are shown in Table III for hypothetical 1-kt detonations. The column E_v is found from $1/2 P_v(V_o - V_v)$ where V_o is the unshocked specific volume and V_v is the specific volume the materials display when shocked by pressure, P_v . ΔH_v is the energy left behind after the material expands, assuming the unloading adiabat is identical to the Hugoniot equation-of-state. This approximation is in error because, at very low pressures, the specific volume of gas greatly exceeds the specific volume of unshocked rock. Less energy is actually left behind than calculated by the method. The error is not thought to be larger than a few percent.

Table III. Thermodynamic properties and calculated vaporization radius for five rock types.

Medium	ρ , g/cm ³	ΔH_v , cal/g	P_v , Mbars	E_v , cal/g	R_v , cm
Alluvium	1.52	2800	0.675	3406	225
Granodiorite	2.67	2800	1.8	4205	183
Tuff (Dry)	1.76	2800	0.865	3475	216
Tuff (Saturated)	1.97	2800	1.1	3577	206
Salt	2.24	1185	0.840	2133	225

⁵Cherry, J. T., Computer Calculations of Explosion-Produced Craters, Rpt. UCRL-14998, Preprint, LRL, Livermore, California., July 1966.

Figure 2 shows the various relationship between P_v , E_v , H_v and the nature of the approximation. R_v , the radius of vaporization, varies directly with the cube root of the explosion energy, and all other quantities are intensive.

Fig. 2. The relationship between ΔH_v , P_v , E_v , and the expansion assumptions used in calculating P_v . E_v is the diagonally hatched area. ΔH_v is the stippled area, the solid curve is the Hugoniot equation-of-state, and the dashed curve is the actual expansion adiabat.

DETERMINATION OF $\bar{\gamma} - 1$

The information in Table III can be used to derive values for the proportionality constant, $\bar{\gamma} - 1$, by substituting into Eq. (2). The substitution leads to the following:

$$\frac{4\pi R_v^3 P_v}{3W} = \bar{\gamma} - 1, \quad (10)$$

where $W = 1 \text{ kt} = 10^{12} \text{ cal}$, if R_v is used from Table III. The approximations involved are: kinetic energy is ignored, and density is uniform and equal to the initial density of the material, and pressure is equal to the vaporization pressure. In fact, what has been done is to use a time-dependent hydrodynamic calculation to determine the amount of gas formed; then the time dependent processes are stopped, all the material is restored to static homogenous conditions, and the expansion of the gas is treated as if it proceeded reversibly. It must be emphasized that $\bar{\gamma}$ calculated this way is not related to γ^+ , and that $\bar{\gamma}$ applies under no other conditions of expansion — that is, as the expansion proceeds, the ratio of PV to W will generally become smaller and smaller as more and more work is done on the surroundings, whereas the ratio of PV to E will vary only slightly. The values of $\bar{\gamma}$ derived from Eq. (10) are very often misunderstood and badly misused. For example, if a value of $\bar{\gamma}$ from the Appendix were used to describe the cavity gas 10 msec after detonation, the product of PV would be almost twofold too large.

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THE MEDIUM INDEPENDENT EQUATION

By using the appropriate values for γ^+ , $\bar{\gamma}$, and P_v from the Appendix, derived as described in the preceding sections, Eqs. (8) and (9) can be numerically evaluated. The results of such an evaluation are presented in Table IV. The quantities for dolomite are presently unknown and not included.

Table IV. Cavity proportionality constants.

Medium	C	B	C/B
Alluvium	89.0	0.939	94.8
Tuff	97	0.975	99.5
Granite	103	1.03	100
Salt	96	0.986	98.4

If all the approximations are valid, the ratio of C/B should be identical for all media. The observation is that the minimum range from the smallest to largest of the ratio is less than 6% and is thus comparable to the standard deviations of measurement in a single medium (See Table II).

The equation

$$R_c = 100 \left[\frac{(\bar{\gamma} - 1) P_v^{\frac{1}{\gamma^+} - 1} W}{(\rho h)^{\frac{1}{\gamma^+}}} \right]^{1/3} \quad (11)$$

would thus appear to fit all observations within the accuracy of the observation and deviation from detonation to detonation.

Figure 3 is a graphic summary of all of the data from the Appendix and is plotted according to Eq. (11). It is gratifying that the best fit line through the data point falls as close to the point 0,0 as it does.

Fig. 3. Observed cavity radius, R_c , in meters, plotted against

$$100 \left[\frac{(\bar{\gamma} - 1) P_v^{\frac{1}{\gamma^+} - 1} W}{(\rho h)^{\frac{1}{\gamma^+}}} \right]^{1/3},$$

where W and h are measured in kilotons and meters for each event, and ρ , P_v , $\bar{\gamma} - 1$, and γ^+ are derived for each medium. See text for method and units.

Data from the 30 events in alluvium were examined for possible effect of depth of burst and W on the constant, C, in Table II. The 15 shallowest and deepest events were selected and averaged with the following results:

	<u>C</u>	<u>σ</u>
Fifteen shallowest (av h = 149 m)	87.3	± 8.8
Fifteen deepest (av h = 251 m)	90.8	± 7.3

If there were a large effect of a constant shear strength on cavity growth, then smaller cavities should be observed, compared to those calculated with Eq. (3), at the shallower depths. In other words, the effect of medium strength should be to make the approximation of Eq. (3) incorrect because the cavity walls would support a higher pressure than that simply arising from gravity. Note that the difference in the shallowest and deepest shots is not significant, so it would appear that either the shear strength is very small compared to overburden pressure or varies directly with the overburden pressure. Data from triaxial tests tend to support the latter conclusion.

The same 30 events were divided into two groups of least and greatest yield and the average C derived. Results can be summarized as follows:

	<u>C</u>	<u>σ</u>
Fifteen least yield (av W = 1.28 kt)	86.7	± 8.6
Fifteen greatest yield (av W = 8.1 kt)	91.4	± 7.8

These differences in C are not statistically significant. It should be noted that the 15 shallowest events and 15 lowest yield events include 12 common experiments.

ERRORS

The errors in the determination of C derive from:

- a) errors in determination of W
- b) errors in determination of cavity boundary (R_c)
- c) errors in composition (ρ and α) and
- d) errors in point of burst (R_c and DOB).

Best estimates of errors in determination of W indicate $\pm 10\%$ as a realistic maximum. This would affect C to $\pm 3.2\%$. Since the one standard deviation error on W is probably more nearly 2 or 3%, it seems unlikely that the standard deviation in C would be more than 1%.

Errors in the determination of cavity boundary and point of burst, both of which influence determination of R_c , can be obtained by comparison of separate drill hole determinations at the same event site. A cursory analysis of several events indicates that there is an absolute uncertainty in determination of R_c of about 1 m. For yields of 0.1 kt, this amounts to a 10% error in R_c , for 1 kt, about 7%, and for 20 kt, 3%.

Errors in variation in composition influence both α and ρ . The error in ρ cannot exceed 20%. ($\rho = 2.5 \pm 0.5$, or $\rho = 2.0 \pm 0.4$). Therefore, for $\alpha = 0.3$, the error in R_c from averaging the overburden density can lead to errors as large as 5.6%. The standard deviation from this source of error should not exceed 2%.

As shown in the Appendix, all alluvium events were assumed to have occurred at places where the water content was 12%. However, the measured H_2O content in alluvium ranged from 8% to more than 20%, but these measurements are considered very unreliable. This leads to minimum and maximum values of α of 0.305 and 0.284. This range would lead to a variation of R_c of 25% or, if the water content is randomly variable, to an error in R_c of $\pm 12\%$ and a standard deviation of about 4%.

In summary, the standard deviations should be:

<u>Source</u>	<u>Deviation</u>
W	1%
R_c	3-7%
α (H_2O)	4%
ρ	2%

The observed standard deviation of C from the average for alluvium of 8.1% is in rough agreement with the sum of the expected errors.

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CONCLUSIONS

Cavities produced by nuclear explosions can be accurately described provided that water content, medium density, and explosive energy are known. The equation

$$R_c = 100 \left[\frac{(\bar{\gamma} - 1) P_v \frac{1}{\bar{\gamma}} - 1}{(\rho h)^{\frac{1}{\bar{\gamma}}}} W \right]^{1/3}$$

describes results of 46 nuclear detonations in tuff, alluvium, salt, and granite to an accuracy which enables cavity radius and other variables to be determined. The adiabatic expansion coefficient, $\bar{\gamma}$, depends strongly on the water content of the medium. There is no indication that cavity size depends on the strength of the rock medium in which the explosion is detonated. This result is certainly unexpected and may be a consequence of simple functional dependence between in situ material strength and one of the variables in Eq. (10). The most likely relationship would seem intuitively to be between h and shear strength.

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APPENDIX: DATA USED IN THE ANALYSIS OF CAVITY RADII.

Alluvium $\rho_o = 1.9 \text{ g/cm}^3$; $\text{H}_2\text{O} = 12\%$; $\bar{\gamma} = 1.125$; $\alpha = 0.296$;
 $(\bar{\gamma} - 1) = 0.83$; $P_v = 0.75 \text{ Mbars}$; $B = 0.939$

Event	Depths of burst (h), meters	Yield (W), kt	Cavity radius (R_c), meters	C	C/B
1	60	0.019	6.7	102	109
2	89	0.13	9.8	88	94
3	150	0.24	9.4	81	86.3
4	149	0.36	13.1	98	104
5	181	0.47	11.3	82	87.4
6	131	0.71	15.5	89	94.8
7	166	0.83	12.2	71	75.6
8	155	1.4	16.5	79	84
9	167	1.5	17.1	82	87.4
10	164	1.6	18.6	87	92.8
11	157	1.9	20.7	90	95.9
12	227	2.2	19.5	90	95.9
13	211	2.5	18.9	83	88.4
14	182	2.6	22.9	94	100
15	227	2.8	19.5	84	89.4
16	181	2.8	24.7	99	105
17	226	2.9	25.9	109	116
18	193	3.3	21.6	83	88.5
19	218	4.4	23.5	85	90.5
20	153	4.5	26.5	87	92.7
21	150	4.8	25.3	80	85.3
22	193	6.2	29.9	93	99.1
23	319	6.5	27.4	98	104
24	256	8.3	27.7	85	90.5
25	303	9.9	33.5	102	108
26	226	11.0	36	97	103
27	224	11.3	33.5	90	95.9
28	305	11.8	32.6	94	100

APPENDIX - Alluvium (Continued)

Event	Depths of burst (h), meters	Yield (W), kt	Cavity radius (R_c), meters	C	C/B
29	226	12.4	30.2	79	84
30	413	21.5	34.7	90	95.9
<hr/>					
<u>Tuff</u>	$\rho_o = 1.9 \text{ g/cm}^3$; $H_2O = 15\%$; $\gamma^+ = 1.14$; $\alpha = 0.292$; $(\bar{\gamma} - 1) = 0.92$; $P_v = 0.99 \text{ Mbars}$; $B = 0.975$				
31	274	1.8	19.8	101	103
32	191	2.0	21.6	89	91.4
33	402	2.7	19.8	99	101
34	403	3.0	21.3	103	106
35	212	3.3	20.4	79	81.0
36	227	4.5	26.8	95	97.5
37	283	5.4	28.0	100	102
38	227	5.6	30.2	100	102
39	311	6.7	27.7	95	97.5
40	544	20.4	35.4	98	100
41	301	22.0	44.2	101	103
<hr/>					
<u>Granite</u>	$\rho_o = 2.7 \text{ g/cm}^3$; $H_2O = 1\%$; $\gamma^+ = 1.03$; $\alpha = 0.324$; $(\bar{\gamma} - 1) = 1.11$; $P_v = 1.81 \text{ Mbars}$; $B = 1.03$				
42	286	5.4	19.2	99	96
43	367	13.4	27.1	107	104
<hr/>					
<u>Halite</u>	$\rho_o = 2.3 \text{ g/cm}^3$; $H_2O = \begin{cases} 4\% \text{ Gnome, } \gamma^+ = 1.11, \alpha = 0.300 \\ 0\% \text{ Salmon } \gamma^+ = 1.07, \alpha = 0.311 \end{cases}$ $(\bar{\gamma} - 1) = 0.957$; $P_v = 0.840$; $B = 0.986$				
44 (Gnome)	361	3.1	18.7	96	97.5
45 (Salmon)	828	5.3	16.7	96	97.5

APPENDIX (Continued)

Event	Depths of burst (h), meters	Yield (W), kt	Cavity radius (R _c), meters	C	C/B
<u>Dolomite</u>	$\rho_o = 2.3 \text{ g/cm}^3$; $\text{H}_2\text{O} = \text{nil}$; $\gamma^+ = 1.03$; $\alpha = 0.329$; $(\gamma - 1) = ?$; $P_v = ?$; $B = ?$				
46	402	12	21.3	89	

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