PREDICTION OF CAVITY RADIUS
AND ESTIMATION OF CAVITY GAS TEMPERATURES
PRODUCED BY A CONTAINED UNDERGROUND NUCLEAR EXPLOSION

By

D. C. Castagnola

C. L. Carnahan

August 1971

Contract AT(29-2)--1229

Prepared for:

U. S. Atomic Energy Commission
Nevada Operations Office
Las Vegas, Nevada

Approved: E. H. Essington
E. H. Essington, Project Manager

TELEDYNE ISOTOPES
Nevada Operations
2765 South Highland Drive
Las Vegas, Nevada 89109

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This document is
PUBLICLY RELEASABLE
Larry E. Williams
Authorizing Official
Date: 06/08/1986

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
leg

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

Predictions of cavity radii and cavity gas temperatures resulting from contained underground nuclear explosions in alluvium tuff, granite, salt and carbonate rocks were made. Relations are given between these cavity parameters and explosion yield, overburden density, depth of burial, geologic medium, and water content of the medium. A plot of observed values of cavity radius versus calculated values showed excellent agreement between the values for tuff and granite. However, calculated values for alluvium tend to be consistently high, possibly because of uncertainty and variations in overburden and rock densities.

Cavity gas temperatures at the end of the hydrodynamic phase of an underground nuclear explosion, when it was assumed the cavity-gas pressure equalled the overburden pressure, were estimated to range from 3500°K to 5000°K for alluvium, tuff, and granite; 3000°K to 6000°K for salt; and 1000°K to 1900°K for carbonate rock. The temperature estimates were based on numerous simplifying assumptions, equations of equilibrium thermodynamics and thermochemical data published in various sources. Published gas equations of state for several natural materials were also used.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT.	i
1.0 INTRODUCTION.	1
2.0 GENERAL DESCRIPTION OF AN UNDERGROUND NUCLEAR EXPLOSION . .	2
2.1 Nuclear Reaction Phase	2
2.2 Hydrodynamic Phase	3
2.3 Quasi-Static Phase	3
2.4 Long-Term Phase.	3
3.0 PREDICTION OF FINAL CAVITY RADIUS	4
4.0 ESTIMATION OF CAVITY GAS TEMPERATURES	15
4.1 Model of Hydrodynamic Phase.	15
4.2 Vapor Pressure Method.	17
4.2.1 Siliceous Rock.	17
4.2.2 Halite.	24
4.2.3 Dry Carbonate Rock.	30
4.3 Equation of State Method	34
4.4 Cavity Gas During Quasi-Static Phase	35
5.0 SUMMARY	43
REFERENCES.	44

LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1 A typical P-V diagram	5
2 Observed versus calculated cavity radius for alluvium, tuff, and granite	12
3 Relations between calculated radius and water content for a 5-kt explosion in alluvium and tuff at a depth of 200 meters	13
4 Cavity radius versus depth of burst for a 1-kt explosion in various rocks.	14
5 Model of the hydrodynamic phase of an underground nuclear explosion	16
6 Relations between cavity temperature and depth of burst for several siliceous rocks calculated by the vapor pressure method	25
7 Relations between cavity temperature and depth of burst for salt calculated by the vapor pressure method.	29
8 Calculated cavity temperature versus depth of burst for carbonate rock.	32
9 Calculated pressure-volume expansion adiabats for dry and saturated alluvium.	36
10 Calculated pressure-volume expansion adiabats for dry and saturated tuff.	37
11 Calculated pressure-volume expansion adiabats for granite and salt.	38
12 Calculated pressure-temperature relations for several rocks determined from gas equations of state.	39
13 Equation-of-state calculated cavity temperature versus depth of burst for several rocks.	40
14 Measured cavity pressure of a 6.5-kt nuclear explosion in alluvium at a depth of 240 meters (Olsen, 1967).	42

LIST OF TABLES

<u>Table</u>		<u>Page</u>
I	Thermodynamic Properties of Various Geologic Media. . .	7
II	Final Cavity Radius Formulae for Various Geologic Media	9
III	$\log_e K$ Equation Coefficients.	20
IV	Amount of H_2O Released from Vaporized Media	23

1.0 INTRODUCTION

Estimations of cavity radius and cavity gas temperature are frequently made in order to predict the extent and degree of hydrologic contamination and the physical, chemical, and spatial distributions of radioactive contaminants produced by contained underground nuclear explosions. These predictions are part of the Supporting Technical Program of the Ground-Water Study Program conducted by Teledyne Isotopes for the Nevada Operations Office of the U. S. Atomic Energy Commission.

This report presents a brief review of underground nuclear explosion phenomenology, review and modifications of a method for predicting cavity radii, and results of estimations of cavity gas temperatures at the end of the dynamic phase of cavity growth. The report provides introductory and background material for future studies treating the chemical and physical states of radionuclides produced in underground nuclear explosions. Relations are given between cavity parameters and explosion yield, overburden density, depth of burial, geologic medium, and water content of the medium. The media considered are alluvium, tuff, granite, halite, and carbonate rock.

Predictions of cavity radii follow the method of Higgins and Butkovich (1967). Cavity temperatures are estimated by two methods, one developed by Butkovich (1967) using graphical equations of state and the other using equilibrium vapor pressure data from various sources.

2.0 GENERAL DESCRIPTION OF AN UNDERGROUND NUCLEAR EXPLOSION

The sequence of phenomena involved in an underground nuclear explosion has been described thoroughly by Johnson (1959). Before presenting the methods used in this report, it is instructive to review the underground explosion phenomenology. Johnson (1959) divides the internal processes into four primary phases which are discussed below.

2.1 Nuclear Reaction Phase

During the nuclear reaction phase, energy of the nuclear explosion is liberated within a few microseconds or less. Initial formation of fission and fusion products occurs, and neutrons are released as a consequence of energy-producing nuclear reactions. Released neutrons are absorbed by device, emplacement, and geologic materials, forming radioactive activation products.

Energy released by nuclear reactions is deposited in the immediate surroundings at extremely high temperature and pressure. As an example, initial temperature and pressure for the Rainier nuclear test were calculated to be about 1,000,000°K and 7,000,000 bars, respectively (Johnson and Violet, 1958).

2.2 Hydrodynamic Phase

Sudden release of energy produces a shock wave which propagates outward in all directions from the center of detonation. Geologic material is vaporized over a radius of several meters under the effect of the shock wave which reaches a peak pressure of about a million bars. Beyond the vaporized region the medium is fused by the propagating shock wave, and as the wave progresses further the medium is crushed and fragmented.

The vaporized rock medium, containing radioactive products and device materials, expands against the fused and fragmented rock, forming a roughly spherical cavity. Time for the cavity to reach its final radius depends on explosive yield, and was about a hundred milliseconds for the Rainier event.

During this phase ionized atoms and electrons combine and chemical reactions between radionuclides and other components of the gas phase occur as cavity temperature decreases. Condensation of more refractory substances occurs. Also cracks can open up in surrounding rock during cavity expansion and melt and gaseous radionuclides can be injected into them (Lynch and Cullimore, 1964).

2.3 Quasi-Static Phase

This phase exists from fractions of a second or seconds to hours after detonation, after the cavity has reached its maximum size. The cavity cools by transport of heat into surrounding rock and by spalling of cavity walls; condensation of cavity vapors continues. Fused rock flows down cavity walls and drops from the ceiling forming a molten pool at the bottom. Internal pressure of the cavity decreases and, generally, the cavity collapses with formation of a chimney of rubble when this pressure can no longer support the weight of overlying rock. The molten pool eventually solidifies into a vitreous mass.

2.4 Long-Term Phase

Collapse of rocks overlying the cavity has stopped, with formation of a chimney of rubble. Slow dissipation of heat through cavity walls occurs (Rawson et al., 1966), and radioactive products undergo growth and decay. Duration of this phase is from time of cavity collapse to days or years.

3.0 PREDICTION OF FINAL CAVITY RADIUS

As mentioned in Section 2.2, the shock wave deposits energy in surrounding rock. As the wave proceeds away from the center of detonation it irreversibly heats the medium by compression (Porzel, 1959). Applying the laws of conservation of mass, momentum, and energy to a steady-state shock moving in stationary material yields the well-known Rankine-Hugoniot equation (Cowperthwaite, 1966):

$$E - E_0 - Q = (P + P_0)(V_0 - V)/2 \quad (3)$$

where E_0 and E are specific internal energies of the rock ahead of and behind the shock wave, respectively;

P_0 and V_0 are pressure and specific volume of the rock ahead of the shock front;

P and V are pressure and specific volume of the material behind the shock front; and

Q is the heat exchanged between compressed rock and its surroundings.

The processes of compression and expansion are shown conventionally in Figure 1. Unloading of material behind the shock is represented by the expansion curve. While unloading, there is loss of internal energy to surrounding materials as a result of heat exchange and work done by the expanding rock. Since the heat transfer processes are relatively slow, compression and expansion are assumed to take place adiabatically ($Q = 0$). The remaining internal energy of the rock after unloading from point (P, V) to its initial conditions (P_0, V_0) is called commonly "waste heat" (Porzel, 1959) and is equal to the area inscribed by the compression and (Hugoniot) expansion curves shown in Figure 1. The waste heat produces a temperature rise in the rock. Vaporization and subsequent gas expansion can bring the material to a final state point (P_f, V_f) .

In underground nuclear explosions, the shock pressure is sufficiently large to deposit enough waste heat to vaporize the rock close to the point

Figure 1. A typical P-V diagram.

of detonation. This vaporized rock becomes the primary driving force that determines the size of the cavity. Butkovich (1967) has developed gas equations of state for materials in which nuclear explosions have occurred. Using these equations of state and experimentally determined Hugoniot curves he obtained values for the pressure, P_V , just sufficient to deposit enough waste heat, ΔH_V , to vaporize the rock within a radius, R_V . Some values for these thermodynamic properties are given in Table I.

Nuckolls (1959) derived the following equation for the cavity radius:

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

where R_c is final cavity radius,
 $\bar{\gamma}$ is an effective expansion coefficient,
 P_V is the shock pressure just sufficient to cause vaporization of the rock after decompression,
 W is explosive yield,
 ρ is average overburden density,
 g is acceleration due to gravity,
 h is depth of burst, and
 $\bar{\gamma}-1$ is a proportionality constant relating the initial energy of the rock vapor to the product $P_V V_V$, where the initial energy is taken equal to W .

The quantity $\bar{\gamma}^+$ is the isentropic expansion coefficient defined by:

$$\bar{\gamma}^+ = - \frac{V}{P} \left(\frac{\partial P}{\partial V} \right)_S \quad (5)$$

By assuming the value $\frac{4}{3}$ for $\bar{\gamma}^+$, Nuckolls arrived at the familiar equation:

$$R_c = \frac{CW^{\frac{1}{3}}}{(\rho h)^{\frac{1}{4}}} \quad (6)$$

which has been shown to be valid for a single medium (Boardman et al., 1964). The constant C changes from medium to medium.

TABLE I
THERMODYNAMIC PROPERTIES
OF VARIOUS GEOLOGIC MEDIA*

Geologic Medium	ρ_o g/cm ³	ΔH_v cal/g	P_v M bars	E_v cal/g	R_v ^{1 kt} 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

* From Higgins and Butkovich (1967).

Higgins and Butkovich (1967), using Nuckolls' equation, have developed a semi-empirical equation for the final cavity radius:

$$R_c = 100 \left[\frac{W(\bar{Y} - 1) P_v^{(1/\bar{Y})} - 1}{(\rho_h)^{1/\bar{Y}}} \right]^{\frac{1}{3}} \quad (7)$$

P_v , $\bar{Y}$, $\bar{Y}$, and ρ depend on water content of the rock. Table II gives values of P_v , $\bar{Y}$, $\bar{Y}$, and ρ interpolated from data given by Higgins and Butkovich (1967) for various geologic media.

The dependence of parameters $\bar{Y}$, P_v , and $\bar{Y}$ on water content in siliceous rocks (alluvium, tuff, and granite) was investigated using data given by Higgins and Butkovich (1967). For these rocks, the following equation for "wet" rock density, ρ_o , can be written:

$$\rho_o = \rho_d + \rho_w e S = \rho_d / (1 - f) \quad (8)$$

where ρ_d is bulk density of dry rock in g/cm³,
 ρ_w is density of water in g/cm³,
 f is weight fraction of water in the rock,
 e is fractional porosity of dry rock, and
 S is fractional extent of saturation, i.e., fraction of pore space occupied by water.

Least-squares analysis of a graph of $\log P_v$ versus $\log \rho_o$ gives the relation:

$$P_v = 0.324 \rho_o^{1.756} \quad (9)$$

where P_v is in megabars and
 ρ_o is in g/cm³

Also, it was found that a graph of $\log (\bar{Y} - 1)$ versus $\log P_v$ is close to a straight line, and least-squares fitting provides the relation:

$$\bar{Y} - 1 = 0.918 P_v^{0.330} \quad (10)$$

TABLE II

FINAL CAVITY RADIUS FORMULAE FOR VARIOUS GEOLOGIC MEDIA

Geologic Material	Fraction of H ₂ O	ρ_o (g cm ⁻³)	P_v (m bars)	$\bar{\gamma} - 1$	γ	$R_c/W^{1/3}$ (meters/KT ^{1/3})
Tuff	0.01	1.77	0.8831	0.8810	1.0330	79.8/h ^{0.323}
Tuff	0.15	1.91	1.0093	0.9207	1.1449	80.6/h ^{0.291}
Tuff	0.20	1.96	1.0562	0.9346	1.1756	80.6/h ^{0.284}
Granite	0.01	2.67	1.818	1.118	1.0330	75.1/h ^{0.323}
Alluvium*	0.01	1.53	0.6837	0.8097	1.0330	76.1/h ^{0.323}
Alluvium*	0.15	1.67	0.7973	0.8518	1.1449	79.4/h ^{0.291}
Alluvium*	0.20	1.72	0.8397	0.8665	1.1756	80.2/h ^{0.284}
Salt	0	2.24	0.840	0.957	1.070	76.9/h ^{0.312}
Salt	0.01	2.25	0.840**	0.957**	1.080	77.1/h ^{0.309}
Carbonate***	0.00	2.7	--	--	--	41.1/h ^{0.250}

* Alluvium is assumed to have an average overburden density of 1.90 g/cm³.

** P_v and $\bar{\gamma} - 1$ for salt with 1 percent H₂O were assumed the same as for dry salt.

*** Carbonate₃ is assumed to have an average overburden density of 2.22 g/cm³.

Substituting equation (9) into equation (10) gives:

$$\bar{Y} - 1 = 0.633 \rho_0^{0.579} \quad (11)$$

$\bar{Y}$ and P_v now can be related to water content, f , through equation (8). For estimation of $\bar{Y}^+$, Higgins and Butkovich (1967) provide a non-linear graph of the quantity $1/3 \bar{Y}^+$ versus f . Using values of $\bar{Y}^+$ obtained from their graph, it was found that a graph of the quantity $(\bar{Y}^+ - 1)/(1 - f)$ versus f is closely linear in the region of interest, $0 \leq f \leq 0.2$. The least-squares equation of this line is:

$$\frac{\bar{Y}^+ - 1}{1 - f} = 0.0235 + 0.980 f \quad (12)$$

which can be rearranged to give:

$$\bar{Y}^+ = 1.0235 + 0.9565 f - 0.980 f^2 \quad (13)$$

Then, assuming $\bar{Y}^+$ is known from equation (13), equations (9) and (11) are substituted into equation (7) to give:

$$R_c = \frac{125 W^{\frac{1}{3}}}{\rho_0^{0.392} - 0.585/\bar{Y}^+} \left(\frac{0.324}{\rho h} \right)^{\frac{1}{3\bar{Y}^+}} \quad (14)$$

where R_c and h are in meters,
 ρ_0 and ρ are in g/cm^3 , and
 W is in kilotons.

Equation (14) distinguishes between ρ_0 , the original rock density near the device, and ρ , the average overburden density; the two densities may be different. If we assume ρ equals ρ_0 , equation (14) becomes:

$$R_c = \frac{125 W^{\frac{1}{3}}}{\rho_0^{0.392} - 0.252/\bar{Y}^+} \left(\frac{0.324}{h} \right)^{\frac{1}{3\bar{Y}^+}} \quad (15)$$

Equations (14) and (15) were used to calculate R_c for forty-three underground detonations in alluvium, tuff, and granite. Values of W and h for these detonations are listed by Higgins and Butkovich (1967). Equation (15) was used for tuff and granite; equation (14) was used for alluvium with ρ assumed equal to 1.9 g/cm^3 . A plot of observed values of cavity radius versus calculated values is shown in Figure 2. The results for tuff and granite were in excellent agreement with observed values of R_c . However, calculated values of R_c for alluvium tended to be consistently high, possibly because of uncertainty and variations in overburden and rock densities.

The equations can now be used to examine the variation of R_c with respect to water content in alluvium and tuff, holding h , W , and dry density constant. Figure 3 shows the relations between R_c and f for these two media over the range $0 \leq f \leq 0.2$. In both cases, $W = 5 \text{ kt}$ and $h = 200 \text{ m}$. Equation (14) was used for alluvium with $\rho = 1.9 \text{ g/cm}^3$ and equation (15) was used for tuff. Both curves show a monotonic, but nonlinear, variation with f . Differences between data presented in Figure 3 and cavity radii calculated from data in Table II are due principally to uncertainties in the curve fitting method used to derive equations (14) and (15). It is apparent that an explosion in "wet" rock will produce a larger cavity than an explosion of the same yield, at the same depth and overburden density, in rock containing less water. This enhancement of cavity size can be regarded also as an apparent enhancement of explosive yield in going from "dry" to "wet" rock.

Figure 4 is a plot of cavity radius for a 1-kt explosion versus depth of burst for various media based on data given in Table II. The cavity radius for an explosion in halite was calculated from equation (7). The cavity radius for carbonate rock was calculated from equation (6) using data from the Handcar nuclear explosion in dolomite (Boardman et al., 1966).

Figure 2. Observed versus calculated cavity radius for alluvium, tuff, and granite.

Figure 3. Relations between calculated cavity radius and water content for a 5-kt explosion in alluvium and in tuff at a depth of 200 meters.

Figure 4. Cavity radius versus depth of burst for a 1-kt explosion in various rocks.

4.0 ESTIMATION OF CAVITY GAS TEMPERATURES

Estimation of cavity gas temperature at the end of the hydrodynamic phase is accomplished with a simplified model of an underground nuclear explosion.

4.1 Model of Hydrodynamic Phase

This model is illustrated in Figure 5. It is assumed that the explosion forms a spherical cavity with final radius, R_c , given by the equations in Section 3, and pressure, P_c , equal to the overburden pressure plus atmospheric pressure:

$$P_c = \rho g_0 h + 1.0 \quad (16)$$

where P_c is in atmospheres,
 ρ is average density of overlying rock in g/cm^3 ,
 g_0 is mean acceleration due to gravity, 981 cm/sec^2 or $0.0968 \text{ atm-cm}^3/\text{m-g}$, and
 h is depth of burst in meters.

The following is assumed about the composition and nature of the various geologic media considered:

1. Alluvium, granite, and tuff consist solely of SiO_2 and H_2O .
2. Halite consists of NaCl and H_2O .
3. Carbonate rock consists of CaCO_3 .
4. Chemical interactions between components of the cavity gas and influence of vaporized device and emplacement materials are negligible.
5. The cavity gases behave as an ideal gas mixture.

To calculate the cavity gas temperatures, two methods will be employed, one using vapor pressure and other thermodynamic relations and the other using gas equations of state (Butkovich, 1967).

Figure 5. Model of the hydrodynamic phase of an underground nuclear explosion.

4.2 Vapor Pressure Method

Here the cavity temperature at the end of the hydrodynamic phase is assumed to be the temperature at which liquid rock is in equilibrium with its vapor. (The pressure exerted by a vapor phase in equilibrium with a liquid phase is called the vapor pressure of the liquid, and, at any temperature below the critical temperature, is independent of the amount of liquid present.) At this stage of cavity formation, it is assumed also that steam produced in zones beyond the vaporized zone does not work its way into the region of expanding cavity gases. Escape of steam from the molten rock lining the cavity is believed to be slowed by viscosity and surface tension of the melt; thus, it should play little part in determining cavity size and temperature at the end of the hydrodynamic phase (Porzel, 1959). Eventually, however, it appears that most of this steam plus steam released from the vaporized rock become the primary component of the cavity gas (Kennedy, 1959 and Olsen, 1967).

4.2.1 Siliceous Rock

For explosions in alluvium, granite, and tuff (siliceous rocks), cavity pressure is assumed equal to the sum of the vapor pressure of SiO_2 and the pressure of steam (not in equilibrium with liquid water) released from vaporized rock.

At the end of the hydrodynamic phase, cavity pressure is given by:

$$P_c = P_{\text{SiO}_2} + P_{\text{H}_2\text{O}} \quad (17)$$

where P_c is total pressure of cavity gas,
 P_{SiO_2} is vapor pressure of SiO_2 , and
 $P_{\text{H}_2\text{O}}$ is pressure of steam released from vaporized rock.

Also, P_c equals overburden pressure given by equation (16).

According to Brewer (1953), solid SiO_2 vaporizes to gaseous SiO and O_2 . It is assumed that the same decomposition of SiO_2 occurs upon vaporization from the liquid phase. Taking into account possible decomposition

of gaseous H_2O , the cavity gas at high temperatures is assumed to consist of a mixture of SiO , O_2 , H_2O , Si , O , H_2 , H , and OH .

The equations required to determine the equilibrium composition of the gas mixture are obtained from equilibrium and mass-balance considerations. The following equilibria are considered, where l = liquid and g = gas:

P 's are partial pressures of components of the gas phase and K 's are thermodynamic equilibrium constants associated with the chemical reactions.

The K 's for a given temperature are evaluated from the standard free energy changes of the chemical reactions at equilibrium:

$$\Delta F_T^0 = -RT \log_e K \quad (24)$$

where ΔF_T^0 is standard free-energy change at temperature T ,

R is the universal gas constant,

T is absolute temperature, and

K is an equilibrium constant at temperature T .

Since ΔF_T^0 and K are functions of T , the usual series expansion can be written expressing $\log_e K$ in terms of T :

$$\log_e K = a + b \log_e T + c \times 10^{-3} T + \frac{d \times 10^3}{T} + \frac{e \times 10^6}{T^2} \quad (25)$$

Coefficients in equation (25) were evaluated using free energy and other thermodynamic data reported in various sources (Glassner, 1957; Lewis et al., 1961; Handbook of Chemistry and Physics, 1968; Chem. Rev. 61, 257, 1961; Chem. Rev. 52, 1, 1953; and Dergazarian et al., 1960). Equation (25) was assumed to be valid for temperatures beyond the range of applicability of thermodynamic data cited in the references. Table III gives the values of the coefficients for various equilibria.

Conservation of matter provides the following relations for the gas phase:

$$N_{Si}^o = N_{SiO} + N_{Si} \quad (26)$$

$$N_O^o = N_{SiO} + 2N_{O_2} + N_O + N_{H_2O} + N_{OH} \quad (27)$$

$$N_H^o = 2N_{H_2O} + 2N_{H_2} + N_H + N_{OH} \quad (28)$$

Also, from the chemical formulas for SiO_2 and H_2O :

$$N_H^o = 2N_{H_2O}^o \quad (29)$$

$$N_O^o = N_{H_2O}^o + 2N_{Si}^o \quad (30)$$

$$N_{H_2O} = N_{H_2O} + N_{H_2} + \frac{1}{2} N_H + \frac{1}{2} N_{OH} \quad (31)$$

In equations (26) to (31), N_x represents number of moles of substance x, and superscript o denotes an invariant total quantity.

Ideal gas behavior is assumed and the mass-balance equations are rewritten in terms of partial pressure:

$$P_{Si}^o = P_{SiO} + P_{Si} \quad (32)$$

$$P_O^o = P_{SiO} + 2P_{O_2} + P_{H_2O} + P_{OH} \quad (33)$$

$$P_H^o = 2P_{H_2O} + 2P_{H_2} + P_H + P_{OH} \quad (34)$$

where T is absolute temperature ($^{\circ}\text{K}$) of the cavity gas at the end of the hydrodynamic phase.

$P_{\text{H}_2\text{O}}^0$ is the partial pressure the steam would exert at this time if H_2O did not decompose. Values for $M_{\text{H}_2\text{O}}^0$, f , ρ , and $R_v^{1/\text{kt}}$ obtained or estimated from data given by Higgins and Butkovich (1967) are presented in Table IV along with relations for $P_{\text{H}_2\text{O}}^0$ as a function of T and h . These relations are derived from equations (39), (40), and (41).

Finally, cavity temperature as a function of depth of burst is computed as follows:

1. Combination of mass-balance equations (32) to (37) gives:

$$P_{\text{H}_2\text{O}} = \frac{(L-J) P_{\text{H}_2\text{O}}^{1/2} - D}{2 I} \quad (42)$$

where $D = 4P_{\text{Si}} + 2P_{\text{SiO}} - 4P_{\text{O}_2} - 2P_{\text{O}}$

$$I = K_4 / P_{\text{O}_2}^{1/2}$$

$$J = (I K_8)^{1/2}$$

$$L = K_6 / J$$

2. A temperature, T , is assigned and the K 's are evaluated from equation (25).
3. An initial estimate of P_{O_2} is made by assuming $P_{\text{SiO}} = 2P_{\text{O}_2}$ and solving equation (18):

$$P_{\text{O}_2} = (K_1/2)^{2/3}$$

4. Using this initial estimate of P_{O_2} , the quantities P_{Si} , P_{SiO} , P_{O} , D , I , J , and L are calculated and $P_{\text{H}_2\text{O}}$ is determined from equation (42).
5. P_{H_2} , P_{H} , and P_{OH} are then calculated from the equilibrium equations.
6. P_c is calculated from equation (38) and the depth of burst, h , from equation (16).

TABLE IV
AMOUNT OF H₂O RELEASED FROM VAPORIZED MEDIA

Geologic Medium	f	ρ (g cm ⁻³)	R_v lkt (meters)	$M_{H_2O}^0/W$ (grams/kt)	$P_{H_2O}^0$ (atm)
Tuff (Dry)	0.01	1.77	2.15	7.39×10^5	$1.58 \times 10^{-6} h^{0.968} T$
Tuff	0.15	1.91	2.09	1.09×10^7	$2.28 \times 10^{-5} h^{0.873} T$
Tuff (Saturated)	0.20	1.96	2.07	1.45×10^7	$3.02 \times 10^{-5} h^{0.851} T$
Granite	0.01	2.67	1.83	6.87×10^5	$1.76 \times 10^{-6} h^{0.968} T$
Alluvium (Dry)	0.01	1.53	2.28	7.58×10^5	$1.87 \times 10^{-6} h^{0.968} T$
Alluvium	0.15	1.67	2.20	1.12×10^7	$2.43 \times 10^{-5} h^{0.873} T$
Alluvium (Saturated)	0.20	1.72	2.18	1.49×10^7	$3.14 \times 10^{-5} h^{0.851} T$
Halite	0.01	2.25	2.25	1.07×10^6	$2.55 \times 10^{-6} h^{0.926} T$

7. $P_{H_2O}^0$ is then calculated from the corresponding equations given in Table IV using the assigned T and calculated h.
8. $P_{H_2O}^0$ is also calculated from equation (37).
9. Another value for P_{O_2} is estimated and the above steps repeated until $P_{H_2O}^0$ determined in step (7) equals $P_{H_2O}^0$ determined in step (8).

Estimates of cavity temperature versus depth of burst as determined by this method are shown in Figure 6 for various siliceous rocks. It should be noted that the cavity temperature at the end of the hydrodynamic phase is a function of the depth of burst and independent of the device energy yield. Cavity temperatures at this phase range from 2,700°K to 4,500°K. The higher the water content of a rock the lower the temperature for a given depth of burst.

4.2.2 Halite

For an explosion in halite, total cavity pressure is assumed equal to the sum of the vapor pressure of NaCl and pressure of steam released from vaporized rock. Steam is assumed to behave as an ideal gas not in equilibrium with liquid water.

At the end of the hydrodynamic phase, cavity pressure is given by:

$$P_c = P_{NaCl} + P_{H_2O} \quad (43)$$

where P_c is cavity pressure (equal to the overburden pressure),
 P_{NaCl} is vapor pressure of NaCl, and
 P_{H_2O} is pressure of steam released only from vaporized halite.

The equations required to determine the equilibrium composition of the cavity gas are obtained from equilibrium and mass-balance considerations.

For salt with one percent water by weight, the following equilibria are considered:

Figure 6. Relations between cavity temperature and depth of burst for several siliceous rocks calculated by the vapor pressure method.

where P's are partial pressures of components of the cavity gas and

K's are equilibrium constants evaluated by equation (25) using values of the coefficients given in Table III.

The mass-balance equations in terms of partial pressures are:

$$P_{\text{Na}}^0 = P_{\text{NaCl}} + P_{\text{Na}} \quad (51)$$

$$P_{\text{Cl}}^0 = P_{\text{NaCl}} + 2P_{\text{Cl}_2} + P_{\text{Cl}} \quad (52)$$

$$P_{\text{O}}^0 = 2P_{\text{O}_2} + P_{\text{O}} + P_{\text{OH}} + P_{\text{H}_2\text{O}} \quad (53)$$

$$P_{\text{H}}^0 = 2P_{\text{H}_2} + P_{\text{H}} + 2P_{\text{H}_2\text{O}} + P_{\text{OH}} \quad (54)$$

Also, from the chemical formulas for NaCl and H₂O:

$$P_{\text{H}}^0 = 2P_{\text{H}_2\text{O}}^0 \quad (55)$$

$$P_{\text{O}}^0 = P_{\text{H}_2\text{O}}^0 \quad (56)$$

$$P_{Na}^0 = P_{Cl}^0 \quad (57)$$

$$P_{H_2O}^0 = P_{H_2O} + P_{H_2} + \frac{1}{2} P_H = \frac{1}{2} P_{OH} \quad (58)$$

P_x represents partial pressure of substance x, and superscript o denotes an invariant total pressure.

Cavity pressure, P_c , is equal to the sum of the partial pressure of components of the cavity gas at the end of the hydrodynamic phase:

$$P_c = P_{NaCl} + P_{Na} + P_{Cl_2} + P_{Cl} + P_{H_2O} + P_{H_2} + P_H + P_{O_2} + P_{OH} + P_O \quad (59)$$

where P_c is equal to the overburden pressure given by equation (16).

From equations (7), (39), and (40), we obtain

$$P_{H_2O}^0 = N_{H_2O}^0 RT/V_c \quad (60)$$

A relation for $P_{H_2O}^0$ in terms of depth of burst, h , and cavity temperature, T , is given in Table IV.

The following computational procedure is used to determine the relation between T and h :

1. Combination of equations (51), (52), and (57) gives:

$$P_{Cl_2} = \frac{1}{2} \left(\frac{K_1 K_2}{K_3 P_{Cl_2}^{1/2}} - K_3 P_{Cl_2}^{1/2} \right) \quad (61)$$

2. For an assigned temperature, T , K_1 , K_2 , and K_3 are calculated by equation (25).
3. Successive approximations of P_{Cl_2} are made until the equality of equation (61) is satisfied. This gives a value for P_{Cl_2} at temperature T .

4. P_{NaCl} , P_{Cl} , and P_{Na} are then calculated from the equilibrium equations (44), (45), and (46).
5. Combination of equations (53) to (56) and (58) gives:

$$P_{\text{H}_2\text{O}} = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad (62)$$

where

$$\begin{aligned} a &= 4A^2 \\ b &= 4AD - (C - B)^2 \\ c &= D^2 \\ A &= K_4/P_{\text{O}_2}^{1/2} \\ B &= (AK_8)^{1/2} \\ C &= K_6/B \\ D &= -(4P_{\text{O}_2} + 2P_{\text{O}}) \end{aligned}$$

6. A value for P_{O_2} is estimated and $P_{\text{H}_2\text{O}}$ is determined from equation (62).
7. P_{H_2} , P_{H} , and P_{OH} are calculated by the equilibrium equations (47) to (49).
8. P_{C} is calculated by equation (59) and h from equation (16).
9. $P_{\text{H}_2\text{O}}^{\circ}$ is then calculated from the T-h relation given in Table IV for halite.
10. $P_{\text{H}_2\text{O}}^{\circ}$ is also calculated by equation (58).
11. Another value of P_{O_2} is estimated and the above steps (5) to (10) are repeated until $P_{\text{H}_2\text{O}}$ determined in step (9) equals $P_{\text{H}_2\text{O}}^{\circ}$ determined in step 10.

The method yields the relation between cavity temperature and depth of burst shown in Figure 7 for dry salt and salt with one percent water content. Thermodynamic data reported in Dergazarian (1960) were used.

Figure 7. Relations between cavity temperature and depth of burst for salt calculated by the vapor pressure method.

4.2.3 Dry Carbonate Rock

In this subsection, two methods for estimating the cavity temperature at the end of the hydrodynamic phase for an explosion in dry carbonate rock will be discussed. For the first method cavity gas is assumed to consist solely of gaseous CaO and CO₂, liberated from thermal decomposition of CaCO₃. Perry's Chemical Engineers' Handbook (1963) gives the following data for the thermal decomposition:

$T(^{\circ}\text{K})$	$P_{\text{CO}_2}(\text{atm})$
1170	1
1431	18.69
1514	39.09

An expression for P_{CO_2} in terms of T is obtained by fitting the data to the following equation:

$$\log_e P_{\text{CO}_2} = a + bT + \frac{c}{T} \quad (64)$$

giving:

$$\log_e P_{\text{CO}_2} = 14.032 + 0.8005 \times 10^{-3}T - \frac{17.530 \times 10^3}{T} \quad (65)$$

where T is absolute temperature in degrees Kelvin and P_{CO_2} is pressure of CO₂ in atmospheres.

Krieger (1965) gives the following vapor pressure data for the sublimation of CaO:

$T(^{\circ}\text{K})$	$P_{\text{CaO}}(\text{atm})$
2517	10^{-3}
3590	1
5265	10^2

An expression for P_{CaO} in terms of T is obtained by fitting the data to the following equation:

$$\log_e P_{\text{CaO}} = a + bT + \frac{c}{T} \quad (67)$$

giving:

$$\log_e P_{\text{CaO}} = 20.051 - 0.6294 \times 10^{-3} T - \frac{63.87 \times 10^3}{T} \quad (68)$$

At the end of the hydrodynamic phase the cavity pressure is assumed equal to the overburden, giving:

$$P_{\text{CO}_2} + P_{\text{CaO}} = \rho g_0 h + 1.0 \quad (69)$$

where ρ is chosen as 2.22 g/cm^3 based on the assumption that CaCO_3 (2.71 g/cm^3) is overlain by water-saturated tuff (1.97 g/cm^3) down to $2/3 h$.

Using equations (65), (68), and (69), the vapor-pressure estimate of the relation between cavity temperature and depth of burst shown in Figure 8 is obtained.

For the second method, data from the Handcar event in dolomite is combined with thermodynamic data for calcite obtained by Krieger (1965). Here the cavity gas produced by the explosion in dolomite is assumed to consist of those components determined by Krieger (1965) for calcite.

Boardman et al. (1966), give the following data for the Handcar event:

Yield	= 12 ± 1 kiloton
Depth of burst	= 402.3 m
Cavity radius	= 21.2 ± 0.8 m

Figure 8. Calculated cavity temperature versus depth of burst for carbonate rock.

Volume of decomposed rock	=	$0.12 \times 10^4 \text{ m}^3$
Average overburden density	=	2.3 g/cm^3
Rock density	=	2.7 g/cm^3

These data applied to equation (6) give the following estimate for cavity radius:

$$R_c = 4.11 \times 10^3 \frac{W^{1/3}}{h^{1/4}} \quad (70)$$

where R_c is in cm, W in kt, and h in m.

Since the volume of decomposed dolomite for this event is estimated to be $0.12 \times 10^4 \text{ m}^3$, the vaporization radius is given by:

$$R_v \leq 2.88 \times 10^3 W^{1/3} \quad (71)$$

An upper limit for cavity-gas density at the end of the hydrodynamic phase is given by the following expression:

$$\frac{4/3 \pi R_v^3 \rho}{4/3 \pi R_c^3} \leq \frac{h^{3/4}}{1.08 \times 10^5} \text{ g/cm}^3 \quad (72)$$

where ρ is the density of dolomite (2.7 g/cm^3).

Use of the upper limit of equation (72) and equation (16) with the data on the thermodynamic properties of calcite, gives a lower-limit relation between cavity temperature and depth of burst. The computational procedures are as follows:

1. Log-log plots of calcite vapor pressure versus vapor density for temperatures from 1000°K to 3500°K are made from the thermodynamic properties of calcite determined by Krieger (1965).
2. Log-log plots of calcite vapor pressure versus temperature are made for upper limit densities calculated by equation (72) for various depths of burst.

3. Cavity pressure is calculated by equation (16) for the corresponding depths of burst used in step (2).
4. Cavity temperature versus depth of burst is obtained by use of plots from step (2), the corresponding cavity pressure determined in step (3), and the cavity density determined in step (1).

Figure 8 also shows the results of this method. The two methods for the treatment of an underground explosion in dry carbonate rock give reasonably similar results in light of the numerous assumptions and approximations. Temperatures are considerably lower than those estimated for siliceous rocks and halite.

4.3 Equation-of-State Method

Butkovich (1967) has approximated gas equations of state for several natural materials which can be used to calculate the adiabatic expansion of gaseous material from an initial state point. His results are in the form of graphical relations between pressure, density, specific internal energy, and temperature. To simplify the calculations, he assumed siliceous rock to consist of SiO_2 and H_2O , where each constituent has its separate equilibria and no interaction between the two occurs. Butkovich's calculations were based on known or assumed equilibrium concentrations of the chemical species resulting from decomposition of the solid material.

For siliceous rock, the species considered by Butkovich (1967) are the gases SiO_2 , SiO , Si_2 , O_2 , O , H_2O , H_2 , and H ; the ions H^+ , O^+ , Si^+ , and e^- ; and solid SiO . For halite, the species considered are the gases Na , NaCl , Na_2 , Na_2Cl_2 , Cl , and Cl_2 ; the ions Na^+ , Cl^+ , and e^- ; and liquid NaCl .

In this subsection the method used to obtain a relation between cavity gas temperatures and depth of burst from these gas equations of state is described. It was assumed that at the end of the hydrodynamic phase the cavity gas generated by a nuclear explosion has expanded adiabatically to a pressure equal to the overburden pressure given by equation (16).

The equations of state provided (1) a graphical relation between the internal energy, E , and gas density, ρ , plotted as lines of constant pressure,

P, and (2) a graphical relation between internal energy and gas temperature, T, plotted as lines of constant pressure.

Next, a graphical relation between the internal energy and pressure for each rock was developed from the E- ρ relation and expansion adiabats shown in Figures 9, 10, and 11. The adiabats were obtained by incrementally decreasing by ten percent the internal energy corresponding to the initial shock point (P_V, ρ_0). For adiabatic expansion of a gas there is no heat exchange with its surroundings ($Q = 0$), consequently $\Delta E = P\Delta V$.

Finally, from the E-P and E-T relation, the P-T relations shown in Figure 12 were obtained. Using equation (16) and the P-T relations, the relations between cavity temperatures at the end of the hydrodynamic phase and depth of burst, shown in Figure 13, were arrived at.

The results of this method for siliceous rocks are in reasonable agreement with those of the vapor pressure method. The equation of state results for halite, however, are about 1500 degrees higher than the vapor pressure estimates, possibly because of the questionable validity of equation (25) for NaCl at very high temperatures, the different chemical species considered, and the assumption of no chemical interactions between the cavity gas components made in the vapor pressure method. The gas equation of state for salt developed by Butkovich (1967) takes into consideration the ions Na^+ , Cl^- , and e^- and the formation of Na_2 and Na_2Cl_2 .

4.4 Cavity Gas During Quasi-State Phase

After the hydrodynamic phase, if no collapse has occurred, the cavity slowly cools by transport of heat into the surrounding medium. Condensation of the more refractory components of the cavity gas continues. It appears, from measurements made by Kennedy (1959) and Olsen (1967) for explosions in tuff, that at some time during this phase, the cavity gas is composed primarily of steam, at a pressure approximately equal to the overburden pressure and a temperature approximately equal to the melting point of the medium (~ 1000 to 1500°C for alluvium and tuff). Calculations indicate that the total amount of steam in the cavity at this time includes steam released from vaporized rock and steam released from molten

Figure 9. Calculated pressure-volume expansion adiabats for dry and saturated alluvium.

Figure 10. Calculated pressure-volume expansion adiabats for dry and saturated tuff.

Figure 11. Calculated pressure-volume expansion adiabats for granite and salt.

Figure 12. Calculated pressure-temperature relations for several rocks determined from gas equations of state.

Figure 13. Equation-of-state calculated cavity temperature versus depth of burst for several rocks.

rock lining the cavity. The cavity gas continues to cool slowly until pressure in the cavity is substantially less than overburden pressure.

Olsen (1967), using pressure transducers located 95 and 123 meters along a pipe extending upward from the shot point, measured cavity pressure following a 6.5-kt nuclear explosion in alluvium at a depth of about 240 meters. Cavity pressure as a function of time after detonation is reproduced in Figure 14. The transducers yielded pressure measurements beginning about 15 seconds after detonation. The measurements show that the pressure decreased slowly from about a minute to ten minutes after detonation. Using the pressure data for this period and considering simple Newtonian cooling of a spherical cavity filled with steam behaving as an ideal gas, Olsen derived the following equation for the temperature of the cavity gas for this period:

$$T = 1410 e^{-0.36t} + 300 \quad (73)$$

where T is temperature in $^{\circ}\text{K}$ and
 t is time in minutes.

At about eight minutes after detonation, the measured pressure began to decrease more rapidly, probably as the result of condensation of steam. At about ten minutes and fourteen seconds after detonation, surface collapse occurred. Olsen found that extrapolation of the pressure data to zero time gave a pressure of about 45 bars. Overburden pressure calculated by equation (16) is 45.7 bars, assuming average density of overlying alluvium was 1.90 g/cm^3 .

Figure 14. Measured cavity pressure of a 6.5-kt nuclear explosion in alluvium at a depth of 240 meters (Olsen, 1967).

5.0 SUMMARY

Equations for predicting the cavity radius resulting from underground nuclear explosions in alluvium, tuff, granite, salt, and carbonate rock are presented. In the case of siliceous rock, Nuckolls' equation (4) for R_c is used as a starting point, and, with data published by Butkovich and Higgins (1967), a new set of equations (14) and (15) are derived in which the critical parameters are yield, depth of burst, dry rock density, water content of the rock, and overburden density if it is significantly different from rock density. It is shown that the new set of equations adequately predicts cavity radii for detonations in tuff and granite, and somewhat less satisfactorily in alluvium. The new equations also provide a means for quantitatively and directly assessing the effects of changing water content on cavity radii in siliceous rocks.

Using the corresponding equations for R_c , thermodynamic vapor pressure data, and gas equations of state developed by Butkovich (1967), cavity temperatures are estimated at the end of the hydrodynamic phase of contained underground nuclear explosions in alluvium, tuff, granite, halite, and carbonate rock. Simplifying assumptions made to obtain relations between cavity gas temperatures and depth of burst include: (1) cavity gas pressure at the end of the hydrodynamic phase is equal to overburden pressure given by equation (16); (2) alluvium, granite, and tuff consist of SiO_2 and H_2O ; (3) halite consists of NaCl and H_2O ; (4) carbonate rock consists of CaCO_3 ; (5) chemical interactions between components of the cavity gas are neglected (except in the equation of state estimate for halite); (6) the nuclear explosion forms a spherical cavity which reaches its final radius at the end of the hydrodynamic phase; and (7) the cavity gases generated by the explosion behave as an ideal gas mixture. Also, expansion adiabats used for the equation of state estimates are calculated assuming initial conditions of rock vapors to be given by P_v and ρ_o , where P_v is the pressure just sufficient to vaporize the rock and ρ_o is the original solid rock density.

REFERENCES

- Boardman, C.R., D.D. Rabb, and R. D. McArthur, 1964, "Responses of Four Rock Mediums to Contained Nuclear Explosions," J. Geophys. Res., 69 3457.
- Boardman, C.R., G.L. Meyer, and D.D. Rabb, 1966, "Macrodeformation Resulting from the Handcar Event," University of California, Lawrence Radiation Laboratory, Livermore, Report No. UCRL-50149.
- Brewer, L., 1953, "The Thermodynamic Properties of the Oxides and Their Vaporization Processes," Chem. Rev., 52, 1.
- Butkovich, T.R., 1967, "The Gas Equation of State for Natural Materials," University of California, Lawrence Radiation Laboratory, Livermore, Report No. UCRL-14729.
- Cowperthwaite, M., 1966, "Significance of Some Equations of State Obtained from Shock-Wave Data," Am. J. Phys., 34, 1025.
- Dergazarian, T.E., et al., 1960, "JANAF Interim Thermochemical Tables," The Dow Chemical Company, Midland, Michigan, December 31.
- Glassner, A., 1957, "The Thermodynamical Properties of the Oxides, Fluorides, and Chlorides to 2500°K," Argonne National Laboratory, Report No. ANL-5750.
- Higgins, G.H., and T.R. Butkovich, 1967, "Effects of Water Content, Yield, Medium, and Depth of Burst on Cavity Radii," University of California, Lawrence Radiation Laboratory, Livermore, Report No. UCRL-50203.
- Johnson, G.W., 1959, "Some Basic Data on Underground Nuclear Explosions," proceedings of the Second Plowshare Symposium, May 1959, Part I, Phenomenology of Underground Nuclear Explosions, University of Calif., Lawrence Radiation Laboratory, Livermore, Report No. UCRL-5675.
- Johnson, G. W. and C. E. Violet, 1958, "Phenomenology of Contained Nuclear Explosions," University of California, Lawrence Radiation Laboratory, Livermore, Report No. UCRL-5124, Rev. I.
- Kennedy, G. C., 1959, "The Early Cavity History of Rainier and Comments on Energy Storage," Proceedings of the Second Plowshare Symposium, May 1959, Part I, Phenomenology of Underground Nuclear Explosions, University of California, Lawrence Radiation Laboratory, Livermore, Report No. UCRL-5675.
- Krieger, F. J., 1965, "On the Thermodynamics of Calcite," The Rand Corporation, Santa Monica, California, Report No. RM-4590-PR.
- Lewis, G. L., and M. Randall, 1961, Thermodynamics, 2nd edition, revised by K. S. Pitzer and L. Brewer, McGraw-Hill Book Company, Inc., New York.

Lynch, E. J., and C. N. Cullimore, 1965, "Spatial Distribution of Radioactive Materials around the Cavity of an Underground Nuclear Detonation," Hazleton-Nuclear Science Corporation, Report No. HNS-1229-47 Supplement 1.

Nuckolls, J., 1959, quoted in Higgins, G. H., and T. R. Butkovich, 1967.

Olsen, C. W., 1967, "Time History of the Cavity Pressure and Temperature Following a Nuclear Detonation in Alluvium," J. Geophys. Res., 72, 5037.

Perry, J. H., 1963, Chemical Engineers' Handbook, 4th edition, prepared by R. H. Perry, C. H. Chilton, and S. D. Kirkpatrick, McGraw-Hill Book Company, New York.

Porzel, F. B., 1959, "Close-in Shock Time-of-Arrival Measurements and Hydrodynamic Yield," proceedings of the Second Plowshare Symposium, May 1959, Part I, Phenomenology of Underground Nuclear Explosions, University of California, Lawrence Radiation Laboratory, Livermore, Report No. UCRL-5675.

Rawson, D., P. Randolph, C. Boardman, and V. Wheeler, 1966, "Post-Environment Resulting from the Salmon Event," J. Geophys. Res. 71, 3507.

DISTRIBUTION LIST - (UNCLASSIFIED)

U. S. Atomic Energy Commission, Nevada Operations Office,
P. O. Box 14100, Las Vegas, NV 89114

Mahlon E. Gates, Manager, NV	
c/o R. R. Loux, Tech. Info. Branch, NV	2
W. R. Cooper, Asst. Mgr. for Plans & Budgets, NV	1
W. D. Smith, Jr., Asst. Mgr. for Engrg. & Logistics, NV	1
Roger Ray, Asst. Mgr. for Operations, NV	1
E. M. Douthett, Dir., Off. Effects Evaluation, NV	3
H. G. Vermillion, Dir., Off. Info. Services, NV	3
D. M. Hamel, NV Technical Library	3
D. T. Schueler, Director, NTSSO, Mercury, NV 89023	1
R. W. Newman, Test Systems Div., NV	1
D. W. Hendricks, Radiological Operations Div., NV	1
CETO Library, (Attn: E. A. Schultz), Mercury, NV 89023	1

U. S. Atomic Energy Commission, Washington, D. C. 20545

R. L. Catlin, Off. Environmental Affairs, USAEC, Wash, DC	1
Maj. Gen. Frank E. Camm, Asst. Gen. Mgr. for Military Application, USAEC, Washington, D.C	2
Dr. M. B. Biles, Dir., Div. of Operational Safety USAEC, Washington, D. C.	2
CETO Library, Div. of Biomed. & Environ. Res., USAEC, Wash, DC	1
J. A. Harris, Jr., Dir., Off. of Info. Services, USAEC Washington, DC	1
J. H. Rubin, AGM for Environment & Safety, USAEC, Wash., DC	1
G. W. Johnson, Div. of Applied Technology, USAEC, Wash., DC	1

U. S. Atomic Energy Commission, Technical Information Center,
P. O. Box 62, Oak Ridge, Tenn. 37830

for UC-35 "Nuclear Explosions - Peaceful Applications" distribution 239

Defense Nuclear Agency

O-I-C, Las Vegas Liaison Office, Field Command, DNA, P. O. Box 2702, Las Vegas, NV 89104	1
Director, DNA (Attn: SPSS), Washington, DC 20301	1
Commander, Test Command, DNA, (Attn: Dr. Benjamin Grote) Kirtland AFB, NM 87115	1

Los Alamos Scientific Laboratory, P. O. Box 1663, Los Alamos,
New Mexico 87544

W. E. Ogle, LASL, Los Alamos, NM	1
E. A. Bryant, LASL, Los Alamos, NM	1
Robert Bradshaw, LASL, Los Alamos, NM	1

Los Alamos Scientific Laboratory (continued)

Charles Browne, IASL, Los Alamos, NM	1
R. H. Campbell, IASL, Los Alamos, NM	1
R. R. Sharp, Jr., IASL, Los Alamos, NM	1

Lawrence Livermore Laboratory, P. O. Box 808, Livermore,
California 94550

R. E. Batzel, LLL, Livermore, CA	1
Fred Holzer, LLL, Livermore, CA	1
J. E. Carothers, LLL, Livermore, CA	1
G. C. Werth, LLL, Livermore, CA	1
H. C. Rodean, LLL, Livermore, CA	1
D. L. Springer, LLL, Livermore CA	1
Tech. Info. Div., LLL, Livermore, CA	3
L. D. Ramspott, LLL, Livermore, CA	1
P. E. Coyle, LLL, Livermore, CA	1
L. S. Germain, LLL, Livermore, CA	1

Lawrence Livermore Laboratory, Mercury, NV 89023

R. D. McArthur, LLL, Mercury, NV	1
----------------------------------	---

Sandia Laboratories, P. O. Box 5800, Albuquerque, NM 87115

C. F. Bild, Org. 9100, SIA	1
J. R. Banister, Org. 9150, SIA	1
M. L. Merritt, Org. 9150, SIA	1
W. D. Weart, Org. 9111, SIA	1
W. C. Vollendorf, Org. 9133, SIA	1

Sandia Laboratories, Mercury, NV 89023

R. D. Statler, Sandia Labs, Mercury, NV	1
---	---

Environmental Research Corporation, 2769 S. Highland,
Las Vegas, NV 89102

W. W. Hays, ERC, Las Vegas, NV	2
--------------------------------	---

Battelle Columbus Laboratories, 505 King Ave., Columbus OH 43201

R. S. Davidson, BCL, Columbus, Oh	1
-----------------------------------	---

Battelle Columbus Laboratories, 2957 S. Highland Dr., Las Vegas, NV
89102

R. G. Fuller, BCL, Las Vegas, NV	1
----------------------------------	---

Holmes & Narver, Inc.

F. M. Drake, Holmes & Narver, Inc., P. O. Box 14340,
Las Vegas, NV 89114

1

Resident Manager, H & N (Mail Stop 605), Mercury, NV 89023

1

Advanced Research Projects Agency, 1400 Wilson Blvd.,
Arlington, VA 22209

S. J. Lukasik, Director, ARPA, Arlington, VA

1

Environmental Protection Agency

R. C. Scott, Federal Water Quality Administration,
EPA, Pacific Southwest Region, 760 Market St.,
San Francisco, CA 94102

1

Regional Dir., Federal Water Quality Administration,
EPA, NW Region, Room 501, Pittock Block, Portland,
Oregon 97205

1

M. W. Carter, Director, Western Environmental Research
Laboratory, EPA, P. O. Box 15027, Las Vegas,
NV, 89114

1

NOAA/Air Resources Laboratory, P. O. Box 14100, Las Vegas,
NV 89114

H. F. Mueller, NOAA/ARL, Las Vegas, NV

1

NOAA/Earth Sciences Laboratory, 3060 S. Highland Drive,
Las Vegas, NV 89102

K. W. King, NOAA/Earth Sciences Lab., Las Vegas, NV

1

Fenix & Scisson, Inc.

M. H. May, Fenix & Scisson, Inc., P. O. Box 50, Las
Vegas, NV 89101

1

Grant Bruesch, Fenix & Scisson, Inc., Mercury,
NV 89023

1

NV Panel of Consultants

Dr. Leo K. Bustad, Director, Radiobiology Lab.,
University of California, Davis, CA 95616

1

NV Panel of Consultants

Dr. Don U. Deere, Consultant Engineering Geology & Rock Mechanics Bivins Lake Estates 2552 SW 14th Drive Gainesville, FL 32601	1
Dr. Lydik S. Jacobsen, Prof. Emeritus, Stanford Univ. 267 Belgreen Place, Santa Rosa, CA 95405	1
Dr. Nathan M. Newmark, Head of Dept. of Civil Engineering, 1108 Civil Engineering Bldg., University of Illinois, Urbana, IL 61801	1
Dr. Carl Kisslinger, Dir., Cooperative Inst. for Research in Environmental Sciences University of Colorado Boulder, CO. 80303	1
Dr. Joseph Lintz, Dept. of Geology, Mackay School of Mines, University of Nevada, Reno, NV 89507	1
Dr. Vincent Schultz, Prof. of Zoology, Washington State University, Pullman, Washington 99163	1
Mr. Thomas F. Thompson, Consulting Engineering Geologist 713 Crossway RD., Bulingame, CA 94010	1
Dr. William G. Van Dorn, Research Oceanography, P. O. Box 109, LaJolla, CA 92037	1
Mr. Lewis G. von Lossberg, Sheppard T. Powell & Assoc., 501 St. Paul Place, Baltimore, MD 21202	1
Dr. James T. Wilson, Dir., Inst. of Science & Technology University of Michigan, 2200 N. Campus Blvd., Ann Arbor, Michigan 48105	1
Mr. Stanley D. Wilson, Shannon & Wilson, Inc. 1105 N. 38th Street Seattle, WA 98103	1
Dr. Paul A. Witherspoon, Dept. of Civil Engineering University of California, Berkeley, 472 Davis Hall, Berkeley, CA 94729	1

Desert Research Institute, c/o USAEC, NV, P. O. Box 14100,
Las Vegas, NV 89101

Dr. George B. Maxey, Desert Research Inst., c/o NV,
Las Vegas, NV

1

Desert Research Institute, Center for Water Resources
Research, Reno, NV 89507

Dr. Paul R. Fenske, DRI, CWRR, Reno, NV

1

National Oceanic and Atmospheric Administration, Environmental
Research Laboratories, 390 Main St., San Francisco, CA 94105

Don Tocher, Earthquake Lab., NOAA/ERL, San Francisco, CA

1

Colorado School of Mines, Golden, Colorado 80401

Maurice Major

1

U. S. Bureau of Mines, Denver Federal Center, Denver, CO 80225

P. L. Russell, USBuM, Denver, CO

1

U. S. Geological Survey, Denver Federal Center, Denver, CO 80225

Dr. W. S. Twenhofel, USGS, Denver, CO

1

R. K. Blankennagel, USGS, Denver, CO

1

Nevada State Engineer's Office, Carson City, NV 89701

Roland Westergard, State Engineer, Water Resources,
Carson City, NV

1