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RESEARCH FOR UNDERSTANDING
AND CONSTRUCTIVELY USING
UNDERGROUND NUCLEAR EXPLOSIONS

Howard C. Rodean

June 6, 1967

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FOREWORD

The first nuclear explosive was detonated in New Mexico approximately twenty-two years ago. This event, Trinity, is the first of 254 nuclear explosions listed in The Effects of Nuclear Weapons¹ for the period 1945-1958, all associated with military applications. It was realized during the days of the World War II Manhattan Project that nuclear energy, including that released in nuclear explosions, could be used in peace as well as in war. However, until ten years ago military requirements provided the only motivation for nuclear explosives development.

The Lawrence Radiation Laboratory (operated by the University of California for the U. S. Atomic Energy Commission) organized a secret meeting in February of 1957 (now declassified and known as the First Plowshare Symposium) at which nonmilitary applications of nuclear explosives were discussed. In July 1957, the Laboratory established the first group with the specific task of exploring engineering uses for nuclear explosives. The United States Atomic Energy Commission subsequently announced the establishment of "Project Plowshare." The center of Plowshare research and development is at the Lawrence Radiation Laboratory (where Plowshare was first suggested) because any consideration of peaceful uses must start with knowledge of the explosive. Four other USAEC Laboratories are now involved in Plowshare work as well as the U. S. Bureau of Mines and U. S. Geological Survey.

The first public disclosures of concepts for civil and industrial applications of nuclear explosives were made in 1958 at the Atoms for Peace Conference in Geneva, and in 1959 at the Second Plowshare Symposium in San Francisco. Industrial organizations did not consider it appropriate to join in experiments at that time, but the Panama Canal Company was interested in the possibility of using nuclear explosives to construct a new sea-level canal. As a consequence, nuclear excavation for civil engineering projects was emphasized during the first years of the Plowshare Program, and the second Plowshare nuclear event, Sedan in 1962, is the largest (100-kt) cratering explosion to date. However, the development of nuclear excavation technology was retarded in 1963 by the Treaty Banning Nuclear Weapon Tests in the Atmosphere, Outer Space, and Under Water. Work has continued, and even increased, on completely contained, underground nuclear explosions (not inhibited by the same treaty) that may be used for industrial purposes. Industry is now demonstrating interest in "Engineering with Nuclear Explosives" (the theme of the Third Plowshare Symposium in 1964²), and the first government-industry experiment with a nuclear explosive, Gasbuggy, will be conducted in New Mexico in the fall of 1967 under the joint technical direction of the Lawrence Radiation Laboratory (for the USAEC), the U. S. Bureau of Mines, and the El Paso Natural Gas Company.

This report summarizes research applicable to Plowshare, and is a companion to a recent report describing industrial applications of contained nuclear explosions.³

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ABSTRACT

This report describes the unclassified research that is directed toward the understanding of underground nuclear explosion phenomena and that is applied to developing constructive applications for nuclear explosions.

The equations of state for geological materials are of fundamental importance in describing the response of these materials to nuclear explosions. These equations are based on geophysical and laboratory measurements of chemical and physical properties, and on theoretical calculations for the high pressure and high temperature conditions not accessible to measurement. Physical measurements of ground motion generated by explosions are used together with the equations of state, chemical and thermodynamic theory, and the laws of continuum mechanics to develop mathematical models used to predict explosion phenomena.

Postshot exploration is necessary to determine the residual explosion effects, such as heat deposition, rock fracturing, and chimney formation. These explorations give physical and chemical clues that aid in the interpretation of the experiment. Furthermore, the residual effects are of interest in many engineering applications.

Safety considerations include airblast and seismic motion that may damage property and radioactivity that may be a health hazard. Significant progress has been made in predicting airblast, ground motion, and radioactivity distribution, but there is need for more work to be done in order that these hazards be predictable with a known statistical accuracy.

Nuclear explosions are intense sources of neutrons; therefore, experiments are conducted to measure neutron cross sections and to produce heavy elements. The heaviest nuclide produced to date has a mass number of 257. The seismic waves generated by nuclear explosions have been used by geophysicists for over two decades to determine the internal structure of the earth with a precision not possible with earthquakes. Finally, research is under way to relate the effects of an explosion to its intended use (in the petroleum industry, for example).

INTRODUCTION

The objective of the Plowshare Program is to make the enormous investment in nuclear explosive technology available for peaceful purposes. Nuclear explosives are potentially useful in civil and industrial projects requiring such large explosions that the compactness and cost of nuclear explosives make them both technically and economically preferable to conventional high explosives. But with any explosive—and particularly with nuclear explosives because of the magnitude of the energy release—the explosion processes involving both the explosive and surrounding rock must be understood and reasonably predictable. Furthermore, undesirable effects, such as the distribution of radioactivity and seismic wave damage, must be understood and predicted with acceptable accuracy. It is for these reasons that research and development are significant parts of the Plowshare Program.

The purpose of this report is to present the highlights of this research and development, and to show how the separately issued reports on such diverse subjects as geological explorations in the field, chemical and physical measurements in the laboratory, and theoretical calculations combine to give an integrated body of useful information. This report emphasizes work done as part of the Plowshare Program, but work sponsored by other programs that contributes to the whole body of information is also included.

Most of the work cited was done at the Lawrence Radiation Laboratory. However, valuable contributions have been made by many other groups; e.g., Los Alamos Scientific Laboratory (neutron cross sections and heavy element synthesis), Sandia Corporation (airblast measurements), U.S. Bureau of Mines (oil shale retorting), U.S. Geological Survey (ground water measurements), U.S. Coast and Geodetic Survey (seismic measurements), Air Force Technical Applications Center (distant seismic measurements), Oak Ridge National Laboratory (radiochemistry), and Savannah River Laboratory (chemical processing).

PROPERTIES OF GEOLOGICAL MATERIALS

Preshot Exploration and Measurement

The characteristics of an underground nuclear explosion are a function of both the energy released and the properties of the surrounding medium. Rock formations tend to be heterogeneous, although there are a few exceptions such as the Tatum Salt Dome in which the Salmon experiment was conducted.⁴ The differences among the "preshot," "last minute," and "postshot" material properties and calculations in the paper⁵ on Salmon free-field motion (see Fig. 1) are evidence that the problem of determining the proper material properties for use in matching computed and measured ground motion is important, even in a relatively simple geological situation.

The significant preshot medium properties include (but are not limited to) density, bulk and shear moduli, elastic and yield stress limits, and chemical composition including water content. These properties generally vary with location, and differ in relative importance as a function of distance from the nuclear explosive. The chemical composition is especially important in the immediate vicinity of the explosive where the rock is vaporized or melted. The elastic and yield stress limits help to determine the extent of the surrounding region where the rock is crushed, cracked, or plastically deformed. Farther out, the speeds of the various elastic waves are functions of the density and the bulk and shear moduli.

The most direct exploration technique is drilling and coring to obtain rock specimens for laboratory tests. This method is limited in that the geology can vary considerably, and samples from one or two drill holes may not be representative. Furthermore, it is necessary to measure in situ as well as core sample properties. The borehole instruments developed for use in the petroleum and mining industries are of use in Plowshare experiments. However, some of these instruments do not have the required characteristics. For example, some will function only in liquid-filled holes, and some geological formations of interest will not hold liquids. Furthermore, the properties of the dry medium are of interest. It is necessary to extend the range of measurement to tens and hundreds of meters. It has also been necessary to improve the accuracy of instruments such as that recently tested for measurement of compressional wave velocity⁶ (see Figs. 2 and 3). Other work is under way to improve methods of measuring shear wave velocity (using a special shear wave source), density (with gamma scattering), and water content (with neutron scattering).

Fig. 1. Calculated and measured vertical motion of ground surface directly over Salmon shot-point. (Fig. 4 of Ref. 5.)

Fig. 2. Representative arrangement of geophone and explosive charges for each of holes cited in Fig. 3. Charges are fired at intervals, and compressional wave travel times to geophone are recorded.

Fig. 3. Depth from top of highest (of the two) holes vs travel time corrected for offset of geophones. Note indication of change in medium properties at about 21 m in agreement with lithological data. In general, this type of measurement does not give such a clear and simple picture because subsurface geology is often more complex than in this case. (Fig. 10 of Ref. 6.)

Laboratory Tests of Preshot Material Specimens

The in situ field measurements must be supplemented by physical and chemical tests in the laboratory. The chemical composition, including water content, affects radioactivity distribution and has a major influence on cavity formation. The initial background radioactivity and the presence of certain trace elements that may become radioactive as a result of neutron capture are of importance in some Plowshare applications. Many of the physical measurements made on core samples are the same as those routinely performed by the petroleum and mineral industries: density, porosity, permeability, water content, etc.

It might appear that little or no new experimental data are needed on the compressibilities of rocks and minerals because these properties have been the subject of much active geophysical research for many years.^{7,8} However, most of the available data are for dense, well-characterized samples whereas most Plowshare explosions occur on a larger scale and must include the naturally existing inhomogeneities. A relatively simple variation of material properties with depth below the surface is illustrated in Fig. 3 on the preceding page: the rather abrupt increase in compressional wave velocity at about 21 m corresponds to a change from vesicular basalt to basalt that is less than 5% vesicular.⁶ Representative variations of compressibility for basalt that is dense, originally dense but cracked, and porous are given in Fig. 4.⁸ The different compressibilities found for trachyte taken from different levels in the same hole are illustrated in Fig. 5.⁸

The compressibility measurements presented in Figs. 4 and 5 were made at static conditions in an assembly in which the sample is subjected to approximately hydrostatic (uniform stress distribution) pressures up to 40 kbar.^{7,8} Triaxial tests (nonuniform stress distribution), performed with a different test assembly, give information on the compressive strength and the stresses at which compressive failure or crushing occur.⁹ The pressures at which rocks vaporize are on the order of megabars; therefore, low stress, static tests must be supplemented with laboratory dynamic tests^{10,11} that approach, but do not attain such high pressures. In these tests, shock waves are generated in the test samples by means of high explosives or gas guns that serve as the energy source. Typical data from such tests are presented in Fig. 6.

Fig. 4. (a) Loading pv (pressure vs specific volume) curves of dense basalt. Samples 1 and 2: cracked basalt, initially dense. Dashed curve and open circles: average of three runs. (b) Loading pv curves of porous basalt. (c) Comparison of loading curves of dense and porous basalt (smoothed curves from Figs. 4a and 4b). Note difference in behaviour at low pressure (especially <4 kbar), and similarity at pressures approaching 40 kbar. (Figs. 1-3 of Ref. 8.)

Fig. 5. Loading pv curves of NTS cracked trachyte. Note difference in properties at various levels. (Fig. A-5 of Ref. 8.)

Fig. 6. Hugoniot measurements for granite. (Fig. 3 of Ref. 12 based on Ref. 10.)

Equation of State

The response of the rocks surrounding an underground nuclear explosion may be determined by means of the three conservation equations of continuum mechanics plus the equation of state. Proper definition of the equation of state is a major problem as emphasized in various papers describing computations with the the SOC^{5,12,13} and TENSOR^{14,15} codes or computer programs.

The problem is reduced to maximum simplicity in the region sufficiently removed from the explosion where the medium response is elastic. The loading and unloading as stresses are applied and removed may be considered reversible in accord with Hooke's law, or may be made slightly irreversible by using a Voigt solid model.¹⁴ The equation of state for this region may be based, for the most part, on the geophysical measurements described on pp. 2 and 3.

The situation is much more complex in the region closer to the explosion where the various elastic limits are exceeded. The loading and unloading processes are not reversible, and the equation of state changes accordingly. A given material element may undergo the following processes: elastic or plastic deformation, crushing (if porous), and shear failure with resultant cracking and bulking. The equation of state used to define such processes are based on the experimental data discussed on pp. 2 through 5 and may employ such concepts as Coulomb friction for crushed material¹² and a generalized von Mises yield criterion for defining the plastic-crushed-elastic region.¹³

The next zone of interest is closer to the explosion where the shock energy deposition is sufficient to melt the material. The equation of state used for this condition is based on the Hugoniot* measurements and the condition that the shear stress is zero.¹²

The rock immediately surrounding the nuclear explosive is vaporized to such an extent that it is the principal constituent of the working gas that forms the cavity.¹⁶ The equation of state for these gases must be determined for pressure and temperature ranges of millions of atmospheres and degrees, respectively, as illustrated in Fig. 7 for salt and Fig. 8 for granite. These data are based on Hugoniot measurements and thermochemical data together with computations using the LRL Ionization Equilibrium Equation of State Code and the HUG code which treat materials as a perfect gas of molecules and ions.¹⁶

*Shock wave (see p. 4).

Fig. 7. Equilibrium equation of state for NaCl. (Fig. 5 of Ref. 16.)

Fig. 8. Equilibrium equation of state for SiO₂ + 1% H₂O by weight. (Fig. 8 of Ref. 16.)

DYNAMIC EXPLOSION EFFECTS

Cavity and Crater Formation

The energy released in a nuclear explosion is sufficient to vaporize the nuclear explosive and to generate an extremely strong shock wave that is propagated outward into the surrounding medium. A portion of the energy transported by the shock wave is dissipated in the shocked material. If enough energy is deposited the material will vaporize (assuming a liquid or solid medium surrounding the explosion). The energy deposited per unit mass decreases as the shock is propagated outward from the explosion. The radius of vaporization is defined as the distance from the center of the explosion (assuming spherical symmetry) at which the shock strength is just sufficient for vaporization (see Fig. 9). At this point, the shock front breaks away from the boundary of the vapor-filled cavity in a manner similar to that shown in Fig. 10.

The first motion of an element of the material surrounding a nuclear explosion is associated with the passage of the shock wave, but the resulting displacement is small compared to that produced by expansion of the cavity vapor. If the explosion is sufficiently far underground, cavity growth continues until its pressure is in equilibrium

Fig. 9. Relationship between energy of vaporization and radius of vaporization for 1 kt for several natural materials. (Fig. 12 of Ref. 16.)

with the surrounding medium. If the medium is homogeneous and cavity collapse does not occur, the result is a near-spherical cavity like that formed by the Salmon Event.⁴ If the explosion is sufficiently close to the surface, the outgoing shock is reflected from the surface as a rarefaction wave and interacts with the cavity to produce the asymmetric shape illustrated in Fig. 11. In this case the cavity continues to expand preferentially upward until equilibrium is reached or venting occurs. A crater will be formed if a significant fraction of the mound particles attain velocities with sufficiently large horizontal components.

Fig. 10. Sample streak photograph showing shock position and cavity radius for brass-covered high explosive shot in water. (Fig. 5 of Ref. 17.)

Fig. 11. Scooter mound (compared with TENSOR calculations) at 1.3 sec. (Fig. 12(c) of Ref. 15.)

Physical Measurement of Ground Motion

In the case of an underground explosion, the most accessible motion for measurement is that of the surface. This motion may be measured by means of acceleration or velocity gages as for the Salmon Event⁵ (see Fig. 1 on p. 3) or by means of photography of targets (Fig. 12) as in the case of Scooter.¹⁵ The Scooter photographs were analyzed visually, a very tedious task. Subsequently, computer programs were developed to read and to analyze the film.¹⁸ They were successfully used for the Pre-Buggy I,¹⁸ Dugout,¹⁹ and other experiments.

Subsurface measurements have been emphasized in the Plowshare Program because surface measurements provide only a small part of the desired information. Instruments have been developed to measure peak pressure, peak particle velocity, and shock position at high stress levels,^{13,20} and stress and particle motion histories at low stress levels.¹³ Such measurements have been made and compared with calculations for the Salmon,^{4,5} Hardhat,^{12,13} Shoal,¹³ and other nuclear explosions^{13,20} as well as for small-scale experiments with high explosives in the laboratory.¹⁷

The slifer* was successfully developed to provide a continuous measurement of shock front position as a function of space and time.²¹ This gage is used in the inelastic region where the shock front is sufficiently strong to deform the medium so as to crush the slifer cable. Most of the data in Fig. 13 were obtained with a slifer. Peak pressure measurements have also been successful in the inelastic region. Early instrument designs used shock transit data and therefore required rather precise orientation,²² while a later design makes use of the depolarization of solids under intense shock in such a way that it is insensitive to orientation.²³ It has not been possible to obtain consistently successful measurements of peak particle velocity in the inelastic region.^{13,20} In the low stress and elastic regions, acceleration, velocity, and displacement histories have been measured for the Hardhat,¹² Salmon,⁵ and other nuclear explosions.¹³ Peak particle velocity and peak radial stress measurements for the Salmon Event^{4,5} are presented in Fig. 14. Tourmaline crystal transducers have been used for stress history measurements in this region for the Hardhat (Fig. 15)^{12,13,15} and other events.^{13,24}

Other physical measurements have been tried with varying degrees of success. For example, one attempt to measure subsurface motion by means of push rods that reached to the surface was not successful.²⁴ On the other hand, cavity pressure measurements in the high explosion Pre-Schooner II experiment showed sufficient promise to warrant further attempts.²⁴ On another occasion, late-time (45 sec to 10 min) cavity pressures were measured following a nuclear explosion.²⁵ A successful cavity pressure history measurement (during and following cavity growth) would be of great value, but has not been accomplished.

*An acronym for "shorted location indicator by frequency of electrical resonance."

Fig. 12. Observed and calculated surface particle velocities at surface ground zero for Scooter Event. (Fig. 10 of Ref. 15.)

Fig. 13. Scaled shock position in granite (X, 2 events), tuff (▲, 3 events) and alluvium (●, 19 events) compared with SOC calculations. (Fig. 15 of Ref. 13.)

Fig. 14. Calculated and measured peak material velocity and peak radial stress for Salmon Event as function of horizontal radial distance from shot-point. (Fig. 9 of Ref. 4.)

Fig. 15. Calculated and measured radial stress at 62 m for Hardhat Event. Position of gauge was not known to desired accuracy. (Fig. 6 of Ref. 15.)

Physical Theory

The basic physical theory of contained underground nuclear explosions was formulated in connection with the third¹ underground nuclear explosion, Rainier, in 1957.^{26,27} The one-dimensional code UNEC²⁸ was used to obtain solutions for shock propagation, rock vaporization and melting, cavity growth, rock deformation, and initial temperature distribution surrounding the fully expanded cavity.^{27,28} UNEC has been superseded by the one-dimensional SOC code,^{5,12,15} and improved equation-of-state data are now available (see pp. 4 through 7). The early assumption that the cavity expands until its pressure is equal to the lithostatic pressure²⁸ is now modified by the evidence that the final cavity pressure is equal to the lithostatic pressure plus some strength effect of the rock.¹⁶ It has been found that simple scaling laws generally give good approximations for cavity size as a function of yield and depth of burial,²⁹ but better results are obtained with the use of computer codes and appropriate equation-of-state data as shown in Fig. 16. Other SOC solutions and experimental data are presented in Figs. 1, 13, 14, and 15.

The phenomena associated with underground nuclear explosions that produce craters are much more complex. As a consequence, the early attempts to predict crater dimensions were empirical in nature and based on similarity relations.³⁰ This approach worked fairly well for a large number of chemical explosions in a given medium (alluvium).³¹ However, four different scaling laws may be derived from similarity theory, and violations of similarity requirements in a series of cratering experiments are usually so severe that it is not possible to decide which scaling law is correct.³² A given empirical relation or scaling law may be used with acceptable error over a small range of conditions, but even today there are not sufficient data to provide a satisfactory predictive capability for large nuclear cratering explosions. Accordingly, a cratering theory based on the laws of mechanics is required. The pertinent phenomena of "free surface spalling" and "gas acceleration" were recognized at an early date,³³ but could not be calculated with the then-available one-dimensional code. Subsequently, a simplified two-dimensional code which combined the laws of mechanics with an empirical frictional coefficient was developed and used with success to calculate craters formed by high explosives.³⁴ This code was superseded by the two-dimensional TENSOR code which uses equation-of-state data (and no empirical coefficients) to give excellent results as demonstrated in Figs. 11, 12, and 17.¹⁵ Crater calculations for nuclear explosions had to await the development of equation-of-state data for the cavity gas.¹⁶ One of the next problems in cratering physics to be solved is that of row charge explosions. A first approximation to this using TENSOR is illustrated in Fig. 18.³⁵

Fig. 16. Calculated cavity growth for Hardhat Event. Measured cavity radius is 19 m.²⁹ (Fig. 8 of Ref. 15.)

Fig. 17. Freefall throwout calculation (compared with observed crater and fallback region) for Danny Boy Event at 100 msec (cavity pressure = 14 bar). (Fig. 17 of Ref. 15.)

Fig. 18. (a) Cylindrical coordinate system approximation to row-charge experiment. (b) Final configuration of TENSOR problem at 90 μ sec. Note "bump" which also appeared between charges in small-scale laboratory row-charge experiments. (Figs. 9 and 13 of Ref. 35.)

Chemical Theory

The 1.8-kt Rainier device was fired in a room with a volume of $7 \times 10^6 \text{ cm}^3$ that contained a mass of material of about 10^6 g . It was estimated that the pressure in this room was about 7,000,000 atm and the temperature about $1,000,000^\circ\text{K}$ a few microseconds after detonation. Under these conditions, the gas in this room consisted of electrons and ions. About 0.2 msec later, shock vaporization was complete and about 88 tons of vaporized tuff (principal components SiO_2 , Al_2O_3 , and H_2O) had been added to the initial ton of cavity gas. Thirty seconds to two minutes later, just before cavity collapse, the SiO_2 and Al_2O_3 had condensed and the cavity gas consisted of steam (H_2O) at a pressure of about 40 atm and an approximate temperature of 1500°C .^{26,27,28,36}

The above ranges of pressures, temperatures, and chemical composition are generally representative of underground nuclear explosions. The equation of state at very early times is similar to that in stellar interiors as illustrated by the application of the IEEOS code (used to compute some of the data in Figs. 7 and 8)¹⁶ to this astrophysical problem.³⁷

At later times when the cavity is nearing its maximum size, the equation-of-state problem is one associated with high temperature chemistry. The chemistry of the Gnome (89% NaCl)³⁸ and Salmon (90% NaCl)⁴ cavity gases is relatively simple compared to that for most other rocks. Silicate rocks, in general, contain 50 to 70 wt % SiO_2 , with the remainder consisting primarily of oxides of aluminum, magnesium, calcium, and iron.³⁹ Water is generally present in significant quantities as in Rainier.^{27,36} In the case of Rainier, the water content was about 15 wt % which is 40 M %. In view of limited thermodynamic data and to simplify calculations, silicate rock is assumed to consist of SiO_2 and H_2O (see Fig. 8 on p. 7) where each constituent has its separate equilibria.¹⁶ The agreement between calculations and experiment indicates that this approximation is satisfactory.

The Handcar explosion in dolomite [$\text{CaMg}(\text{CO}_3)_2$] was the first underground nuclear explosion in which a permanent gas (CO_2) could be generated in large quantities.⁴⁰ This experiment presented a complex problem in cavity gas chemistry. The kind of information necessary to prepare an equation of state for dolomite is illustrated in Figs. 19 and 20. The decomposition temperature of dolomite as a function of pressure is shown in Fig. 19, and the decomposition products of dolomite as it is heated at 100 atm are given in Fig. 20. In addition, the appropriate heats of sublimation, melting, vaporization, and dissociation must be known as well as the heat capacities of all the solids, liquids, and gases involved.

Fig. 19. Phase equilibria in the system $\text{CaCO}_3\text{-MgCO}_3$. Dashed lines show CO_2 pressure, in atmospheres, which is generated when mixtures of CaCO_3 and MgCO_3 are heated at equilibrium in closed vessel. (Fig. 20 of Ref. 40.)

Fig. 20. Chemical changes as dolomite is heated at constant pressure. (Fig. 21 of Ref. 40.)

RESIDUAL EXPLOSION EFFECTS

Heat and Resultant Changes to Geological Materials

The shock wave produced by a nuclear explosion deposits significant quantities of heat in the medium outside the vaporized and melted regions. The calculated temperature distribution (temperature rise above ambient) for the Rainier Event is presented in Fig. 21.^{27,28} It was noted during postshot exploration that there was no trace of the original glass-lined side walls. It is therefore inferred that the heat deposited in and conducted into the cavity walls vaporized the water (15 percent by weight) in the tuff, and the walls imploded into the cavity when the cavity pressure dropped below that of the steam in the walls (after cavity expansion and before collapse).³⁶ There is evidence of the same phenomenon in Gnome where steam pressure (from a water content of 1 or 2%) may have been sufficient to contribute to the implosion, decrepitation, or spalling of about 13,000 tons of salt that was intimately mixed with about 2,400 tons of melt.³⁸ The Salmon salt contained only 0.001 % water, and this phenomenon was not observed in this event.⁴

Temperature surveys have been made of the postshot environment of a number of underground nuclear explosions. It has been determined that 90 to 95% of the energy released by such an explosion remains as residual thermal energy if complete containment is achieved.⁴¹ The Salmon temperature profiles presented in Fig. 22, together with estimates⁴² of the puddle temperature (600°C), indicate that about 90% of the 5.3 kt released was deposited within 50 m of the explosion.⁴ A thermal yield of 4.5 ± 0.3 kt was estimated from measured cavity gas temperatures four, nine, and twenty months after the explosion.⁴² If appreciable quantities of water are present, the maximum temperature of the medium tends toward the boiling point of water,⁴¹ significantly less than the Salmon salt temperature. This tendency is illustrated in Fig. 23 for the Shoal chimney.⁴¹ The solidified melt at the bottom of the cavity was still hot (600°C) at the time of measurement and served as the energy source for convective currents that circulated steam throughout the chimney so as to produce a fairly uniform temperature of about 100°C.

The temperature history of the melt in the nuclear explosion-formed cavity can be inferred by means of chemistry. It appears that the Salmon puddle remained fluid for at least a month because xenon-131, the daughter of iodine-131, was found only in the cavity gas.⁴ Samples of the puddle exhibited fractional crystallization toward the center with NaCl as the principal phase (see Fig. 24). Sample 5, taken toward the center may represent eutectic crystallization of NaCl, CaSO_4 , and Na_2SO_4 .

Fig. 21. Initial Rainier temperature distribution outside fully-expanded cavity. Cavity radius is 19 m. (Fig. 2.8 of Ref. 28 and Fig. 8 of Ref. 27.)

Fig. 23. Shoal temperature profile. Note how temperature in upper part of chimney approaches that of boiling water. (Fig. 8 of Ref. 41.)

Fig. 22. Temperature profile above and below Salmon cavity based on measurements four months after the explosion. (Fig. 8 of Ref. 4.)

SAMPLE NUMBER	DEPTH (m)	SAMPLE NUMBER	DEPTH (m)
1	838.2	8	842.6
2	838.8	9	842.6
3	839.7	10	843.4
4	840.6	11	843.6
5	841.3	12	843.8
6	846.6	13	844.1
7	842.5

Fig. 24. The system $\text{NaCl}-\text{CaSO}_4-\text{Na}_2\text{SO}_4$. Numbers correspond to samples taken from Salmon puddle at various depths in hole PS-1. (Fig. 7 of Ref. 4.)

Macrodeformation and Microdeformation and Fracture of Rock

The shock wave and cavity expansion produce inelastic deformation and fracture of the surrounding rock. After the Gnome Event, melt injection and radiation-damaged salt (from radioactive gases) gave evidence of fracturing out to about 30 m vertically and 60 m horizontally from the shot point.³⁸ This nonspherical pattern is probably associated with horizontal bedding planes in the salt. The fracture pattern around the Salmon cavity (in a homogeneous salt) extended out to about 90 m from the cavity edge, and appeared to be spherical except at the top (around the emplacement hole) and the bottom (under the puddle).⁴ The observed limits of microfracturing (or crushing) and cracking for Salmon compare favorably to the expected limits based on failure criteria associated with the equation of state used in the SOC code (see Fig. 14, p. 11).^{4,5} The average permeability (inferred from cavity pressurization tests) of the microfractured zone (the first 47 m outside the cavity) is about 50 millidarcys, significantly higher than the preshot values of less than 0.1 millidarcy.⁴ It was possible to make individual permeability measurements in the rock outside the Hardhat chimney. It is conceivable that chimney collapse induces a cylindrical fracture pattern that is superimposed upon the basic spherical pattern. However, the scatter of the data points is such that the variation of permeability vs radial distance from the shot point (shown in Fig. 25) is not perceptibly different from a plot of permeability vs horizontal distance from the chimney axis.⁴³ Pressure decay tests of the Handcar chimney (see Fig. 26) indicate a region of altered permeability extending 72 to 104 m from the shot point.⁴⁴ The extent of fracturing outside the cavity and chimney is of interest in some potential applications of nuclear explosives such as natural gas reservoir stimulation. Some sites of interest in this application require explosions at depths of 2,000 to 3,000 m. One question to be answered by future research is, "Will fractures at these depths remain open, or will they 'heal' because of the great lithostatic pressures?"

Petrographic microscope study of shocked rock is a valuable supplement to physical measurements of stress and ground motion (pp. 10 and 11). One useful parameter is the degree of microfracturing. It is shown in Fig. 27 that the degree of fracturing⁴⁵ and the computed peak stress¹² vary with distance from the shot point in a consistent manner. Low pressure phase changes may also serve as pressure indicators. For example, the different optical domains in the anhydrite (CaSO_4) crystals from just outside the Salmon cavity (see Fig. 28) are believed to be associated with a phase transformation that occurs at a pressure of 25 kbar,^{4,46} but which may occur at higher pressures under dynamic conditions.

Fig. 25. Permeability vs radial distance from Hardhat shot-point. (Fig. 3 of Ref. 43.)

Fig. 26. Pressure decay rate vs Handcar chimney air pressure. (Fig. 5 of Ref. 44.)

Fig. 27. Variation of fracture index (relative abundance of microfractures) with preshot distance from Hardhat shot-point. (Fig. 7 of Ref. 45.)

Fig. 28. Appearance of anhydrite grains in postshot sample subjected to shock from Salmon explosion. (a) Plane-polarized light showing cleavage traces and cracks. (b) Same area as (a) with X-nicols showing different optical domains. (Fig. 3a and 3b of Ref. 46.)

Chimney Formation

Of all the contained underground nuclear explosions detonated by the United States, only two are known to have produced permanent cavities: Salmon,⁴ which remained standing (Fig. 29), and Gnome,³⁸ which partially collapsed (Fig. 30). The Salmon cavity walls were sufficiently competent to respond nearly elastically and thereby decouple the subsequent Sterling Event,⁴ and it is believed that the cavity is still standing. The cavities formed by other contained nuclear explosions collapsed at various times following the explosion. The Rainier cavity collapsed to form a chimney (Fig. 31) only a few moments after detonation.²⁷ On the other hand, the Hardhat cavity is believed to have remained standing for 11 hr.²⁹ Cavity collapse is generally detected by means of geophones. Recently the slifer²⁴ (see p. 10) has been adapted to measure the rate at which the collapse progresses toward the surface.⁴⁷ This measurement confirmed that collapse in alluvium is rather massive with propagation rates of about 30 to 60 m/sec. Chimney propagation upward is limited by the strength of rock (Gnome,³⁸ Handcar⁴⁴), bulking of rubble, or surface of the ground.²⁹ If the chimney propagates upward to the surface, as is often the case in alluvium which does not bulk appreciably during collapse, the result is a subsidence crater (Fig. 32).²⁹

A "first principle" predictive capability concerning chimney formation has not yet been developed. It is evident that important parameters are cavity size, the nature and orientation of natural structural weaknesses, the strength of the outgoing shock, and possibly the rarefaction wave reflected from the surface. The chimney radius is about the same as that of the cavity, but its height varies considerably depending upon the bulking and strength characteristics of the rock.²⁹ This is an obvious area for future research because most applications of contained underground explosions are dependent upon chimney formation. Questions associated with explosions thousands of meters deep not only concern fracture healing (see p. 18), but chimney formation itself: "Will chimneys form at such depths even if the rock is inhomogeneous?"

The rubble particle size and shape are of interest in some applications (for example, mining and oil shale) and are functions of the cavity size, distribution of original faults and fractures, mechanical and thermal stresses applied by the explosion, and the breaking and grinding action during collapse. It appears that the particle size distribution (at least in the case of Hardhat according to limited data) may be approximately described by a lognormal distribution.⁴⁸

Fig. 29. The spherical Salmon cavity. (Fig. 2 of Ref 4.)

Fig. 30. The partially-collapsed Gnome cavity. (Fig. 4 of Ref. 38.)

Fig. 31. Schematic cross section of Rainier chimney. (Fig. 3 of Ref. 29.)

Fig. 32. A subsidence crater in alluvium. (Fig. 7 of Ref. 29.)

SAFETY CONSIDERATIONS

Airblast

Ground surface motion is the only mechanism for coupling a portion of the energy of a completely contained underground explosion to the atmosphere. This motion occurs when the explosion-produced shock wave reaches the surface (see the first 100 msec of Fig. 12, on p. 11). This motion produces spalling which, as depth of burial decreases while explosion yield remains constant, results in material being ejected to form a crater.^{15,33,34} If the cavity gas acceleration phase^{15,33,34} also occurs, additional energy is coupled to the atmosphere (see the period following 400 msec in Fig. 12). A third mechanism which produces airblast is that of cavity gas venting⁴⁹ (see Fig. 11, p. 9) which becomes predominant as the depth of burial approaches zero. The complete airblast source description is therefore rather complex, and is the subject of current research. Airblast is of obvious concern in the case of large cratering explosions, and it may have to be considered for very large contained explosions.

Airblast prediction, once the source term is defined, is relatively simple for locations close to the explosion. However, the situation is much more complex at ranges of tens to hundreds of kilometers because various meteorological conditions can cause the sound "rays" to be refracted in such a way that they focus at one or more locations (caustics) on the ground surface with sufficient strength to cause light architectural damage.^{1,2,50} Recently, the first theoretical calculations of sound pressure as functions of time and space in the region of a focus were made.⁵¹ The results of one of the calculations for the 100-kt Sedan Event² are presented in Fig. 33. A close correlation between observed and theoretical signals for a given event at a specific location is unlikely because of random fluctuations in the wind and temperature; therefore, any correlation between experiment and calculations must be on a statistical basis.⁵¹ This is illustrated in Fig. 34, which shows the variability of microbarograph recordings of three 10^6 g high explosive charges fired within a period of 9 min.⁵² At present, there are insufficient wave shape data from large explosions for this purpose.

Airblast caustic and sonic-boom phenomena are very similar with respect to the physics of atmospheric propagation, overpressure levels, property damage thresholds, and psychological reactions, and differ mainly in their source terms. Therefore, some of the techniques and results of sonic-boom research⁵³ may be used to supplement present airblast studies.

Fig. 33. Complete theoretical Sedan signal. Left-hand pressure pulse is that of first caustic (centered at 170 km), and right-hand, second caustic (centered at 165.5 km). Reference value of R is 170 km, so top signal is that received at 164 km, second from top, at 170 km, the third, at 176 km, etc. (Fig. 8 of Ref. 51.)

Fig. 34. Microbarograph traces from three 10^6 -g High Explosive charges fired at Nevada Test Site. Recordings made at St. George, Utah. (a) Shot at $H - 2$ min. (b) Shot at $H + 4$ min. (c) Shot at $H + 7$ min. (Fig. 1 of Ref. 52.)

Seismic Motion

The abrupt, large-amplitude ground motion near an underground explosion is a necessary part of the intended effects of the explosion, but, at greater distances, motion associated with the resulting wave train may result in unwanted property damage. Accordingly, a knowledge of seismic damage criteria for various structures and installations is essential to the Plowshare Program. On the basis of a study of damage to property caused by many high explosive blasting operations and several underground nuclear explosions, it was concluded that the architectural damage threshold (cracking of plaster and masonry) was associated with a ground surface peak velocity of 10 cm/sec independent of frequency (Fig. 35).^{54,55}

This work was used to predict the damage to be expected from the Salmon Event, but there were hundreds of unexpected complaints in the region where the ground motion was less than 10 cm/sec (Fig. 36).⁵⁶ Much of the claimed damage appeared to be real and of recent origin, but it did not seem possible to establish a definite coincidental or noncoincidental relationship between the Salmon Event and individual cases of damage. The 10 cm/sec threshold may be valid for vibration damage to an unstressed building on firm soil, but (it was concluded) the damage threshold can no longer be considered to be a function of peak ground motion alone.⁵⁶ For example, there may be one threshold for vibration damage related to the structure, and another for settlement damage that is a function of both the structure and foundation soil.⁵⁶

A controlled experiment was subsequently initiated with 43 relatively new masonry structures at Mercury, Nevada.⁵⁷ Thorough inspections were made for cracks before and after nuclear explosions as well as during periods of no significant testing activity (Fig. 37). The explosion-induced cracks were no more severe than those caused naturally, explosions did not appear to affect the natural cracking rate between explosions, and the explosion-produced cracks, it appears, may have occurred naturally in a matter of time (triggering). Peak particle velocities of 0.1 to 0.3 cm/sec were sufficient to produce these cracks, and there was some indication that lower frequency motions with these velocities (from larger, more distant explosions) produced significantly fewer cracks.⁵⁷ This study is still under way, and it appears that the natural cracking rate is now decreasing. At present there is no exact method of correlating ground motion and seismic damage. As in airblast (p. 22), it appears that damage predictions must be on a statistical basis because of all the variables of ground motion, construction materials and practices, soil and foundation characteristics, etc. Consequently, the concept of damage threshold should be replaced by that of increasing ground motion, suitably modified for the frequency content of the motion and the resonant frequencies of structures.

Fig. 35. Damage as function of velocity showing independence of frequency. Data replotted from measured displacements assuming simple harmonic motion. (Fig. 1 of Ref. 56.)

Fig. 37. Cumulative cracks and natural cracking rates for masonry buildings at Mercury. (Fig. 11 of Ref. 57.)

Underground nuclear explosions have made possible research on seismic wave propagation to distances of hundreds to thousands of kilometers. Early underground tests indicated that the seismic signal amplitude at a given location is directly proportional to explosion yield,⁵⁸ and later work showed the amplitude to be a weaker function of yield for large explosions.⁵⁹ It was subsequently demonstrated that seismic coupling is medium-dependent (e. g. , relatively weak for alluvium and stronger for granite) and that the propagation path is also significant.^{59,60} One of the most important seismic coupling parameters appears to be dry porosity as shown in Fig. 38 where the "b" displacement (the amplitude of the first cycle in the wave train) is scaled to common values of yield and range.⁶⁰ The importance of propagation path is illustrated by two shots in granite: Hardhat at the Nevada Test Site and Shoal near Fallon, Nevada.⁶⁰ All events shown in this figure occurred at the Nevada Test Site and were recorded at Mina, Nevada except Salmon, Gnome, S. S. Village, and Shoal.⁶⁰ A key parameter in the theory of seismic signal generation is the radius of the inelastic region surrounding the explosion.⁵⁸ This radius is a function of the explosion energy released and the medium equation of state (especially in the transition region between elastic and inelastic behavior), see pp. 4 through 6 and 10 through 12. Figure 39 illustrates that, for a given explosion yield, the inelastic region radius for alluvium, for example, is much smaller than that for a material like granite.⁶⁰

The research discussed in the preceding paragraph is associated with the problem of detecting underground nuclear explosions, and concerns the amplitude of the first (compressional) wave to arrive at the receiving station. The problem of seismic motion pertinent to property damage is more complicated than this because the damage-producing part of the wave train does not appear to be the first arrival, may be a shear wave instead of a compressional wave, and may be a series of waves instead of an individual wave. The problem of computing seismic wave patterns is even more complex than that for airblast (p. 22) because Rayleigh and shear waves as well as compressional waves are present. The Tatum Salt Dome problem (using TENSOR)¹⁴ was studied with respect to downward wave propagation (and subsequent seismic signal detection at the surface 200 to 700 km away), not ground motion at the surface 10 to 30 km away (pertinent to local property damage). Surface motion problems can be run, but SOC and TENSOR are not particularly suited to running problems for seconds-long phenomena.¹³ As in the case of airblast (p. 22), any correlation between theoretical and experimental ground motion would have to be on a statistical basis because of uncertainties in the geological structure.

Fig. 38. Effect of dry porosity on coupling of explosive energy in various media. Extrapolation to calculated full decoupling appears to be conservative, but only experimental data in high dry porosity range can establish its validity. (Fig. 8 of Ref. 60.)

Fig. 39. Summary of strong shock calculations for detonations in various media using SOC computer code. These calculations agree well with experiment except for dolomite (a factor of two or three disagreement) and pumice (no experimental data). (Fig. 10 of Ref. 60.)

Radioactivity

The amounts and kinds of radioactivities produced by a nuclear explosion are dependent on the specific design of the explosive and the chemical environment surrounding it. The two design extremes are a pure fission device which will produce about 2.9×10^{23} fission fragments per kiloton, and a pure thermonuclear device which would produce no fission products but approximately 10^{23} atoms of tritium per kiloton.⁶¹ The excess neutrons produced (about 1×10^{23} neutrons per kiloton for fission, about ten times as many per kiloton for fusion) ultimately interact with the materials of the explosive or of the immediate environment, and may result in the production of other radioactive species.⁶¹ Because fission fragments decay by beta emission to become stable, the chemistry of these species changes with time. The relative contribution of various elements (grouped as volatiles, intermediates, and refractories) to the total fission activities for several times after the explosion is given in Table I.⁶¹ Table II presents an estimate for neutron activation products in basalt (together with some fission products for comparison) assuming a boron blanket-surrounded 1-Mt explosive with 1% of the energy from fission and the remaining from fusion.⁶¹ The fusion reaction would produce about 10^7 Ci of tritium which would have to be considered along with the activation and fission products shown in Table II.⁶¹

Exploration of the Rainier chimney revealed that from 60 to 85% of the gross fission products were trapped in the glass formed by the explosion, and that those materials with gaseous precursors were depleted relative to the nonvolatile species.²⁷ The volatile species were correspondingly enriched in the region outside the melt.²⁷ This is generally representative of explosions in silicate rocks. The Handcar results indicate that there is no apparent gross difference between dolomite and silicate rocks in this respect.⁴⁰ Both Gnome^{38,62} and Salmon⁴ results show that nearly all fission products (except volatiles) are concentrated in the salt impurities (natural and introduced by the device emplacement). These impurities were segregated in black bands at the bottom of the Salmon puddle.⁴

Chemical species in the cavity gas exist as ions at early times, and chemical recombination and condensation occur during the later part of the cavity expansion. The rock surrounding the explosion is generally composed of oxides, for the most part, and the condensation products formed during cavity expansion will also be oxides. Most fission products also condense as oxides. The relative volatilities of the various oxides play an important role in the condensation process and hence in the final location (e. g., puddle or chimney) of the fission products.⁶³ Many tons of iron (from the explosive emplacement) and water (from the medium) are generally present in the cavity gas and react so as to reduce the available oxygen.⁶⁴ Fission products which have less stable oxides than iron will be reduced to a lower oxide or a free element. Therefore, control of cavity gas chemistry may be of interest with respect to some radionuclides.

Table I. Percent contribution of elements to total activity produced in fission.
(Table I of Ref. 61.)

Element	1 sec	10 sec	30 sec	1 min	5 min	10 min	1 hr	1 day
Volatile								
Kr	3.6	3.8	5.0	5.8	4.3	2.5	4.2	—
Xe	4.6	2.6	3.8	4.6	9.0	5.0	3.5	14
Br	2.5	3.3	5.0	6.0	2.2	—	1.0	—
I	3.4	4.0	6.0	7.0	3.5	3.5	7.0	16
Te	1.9	2.7	2.5	2.0	3.5	9.0	14	3.9
Se	1.3	1.5	1.0	—	—	—	—	—
Total	17.3	17.9	23.3	25.4	22.5	20.0	29.7	33.9
Intermediate								
Sn	1.3	1.1	—	—	—	—	—	—
Sb	—	1.0	2.3	3.7	5.0	2.3	2.0	—
Cs	9.5	7.0	7.0	7.0	8.0	8.0	8.0	—
Rb	7.0	8.0	8.0	8.0	11.0	7.0	4.8	—
Mo	—	3.0	6.0	6.0	5.0	7.0	3.0	4.2
Tc	—	1.2	4.0	8.0	5.0	9.0	7.0	—
Total	17.8	21.3	27.3	32.7	34.0	33.3	24.8	4.2
Refractory								
Ba	11	7.0	2.6	2.4	8.0	9.0	8.0	1.1
Sr	11	6.0	4.0	5.0	11	4.0	3.7	6.5
Y	15	11	9.0	8.0	4.6	7.0	5.0	13
Zr	12	12	7.0	3.5	—	—	—	8.6
La	7.0	9.0	8.0	4.0	2.8	9.0	10	1.6
Nb	5.0	10	12	11	8.0	5.0	6.0	18
Ce	2.5	4.7	3.0	1.0	2.5	5.0	4.4	6.6
Pr	—	1.7	3.7	5.0	4.6	3.7	5.0	2.9
Nd	—	—	—	—	—	—	1.0	—
Total	63.5	61.4	49.3	39.9	41.5	42.7	43.1	58.3

Table II. Neutron activation products in basalt.
(Table IV of Ref. 61.)

Nuclide	Half-life	Radiation (MeV)	Curies at t_0
Activation Products			
Si ³¹	2.62 hr	β^- , 1.47 γ , 1.26 (~0.1%)	7×10^7
Fe ⁵⁵	2.7 yr	γ 0.006	7.5×10^5
Fe ⁵⁹	45 day	β^- , 0.27, 0.46 γ , 1.1, 1.28	3.8×10^4
Mn ⁵⁶	2.58 hr	β^- , 2.8, 1.0, 0.6 γ , 0.85, 1.81, 2.13	8.4×10^8
Ca ⁴⁵	165 day	β^- , 0.255 no γ	4.3×10^4
Na ²⁴	15 hr	β^- , 1.4 γ , k , 37, 2.76	1.9×10^8
K ⁴²	12.4 hr	β^- , 3.55, 1.99 γ 1.53 (~20%)	2.8×10^6
P ³²	14.3 day	β^- , 1.7 no γ	1.8×10^5
Fission Products			
Sr ⁹⁰	28 yr	β^- , 0.45 no γ	1.8×10^3
Mo ⁹⁹	66 hr	β^- , 1.2, 0.41 γ , 0.140, 0.75	6.7×10^6
I ¹³¹	8 day	β^- , 0.61 γ , 0.36	1.28×10^6
Nd ¹⁴⁷	11 day	β^- , 0.81 γ , 0.09	7.5×10^5

Nuclear testing moved underground in response to concern about radioactivity in the atmosphere and introduced the problem of ground water contamination. Water samples from drill holes in the vicinity of the early underground tests showed no activity significantly above background.⁶⁵ This is a consequence of most fission products being trapped in the silicate glass, the small amount that is subsequently leached from the glass, and the slow rate of radioactivity migration (relative to that of the water) as a result of ion exchange in most rock materials.⁶⁵ This conclusion has been confirmed by subsequent experience together with theoretical⁶⁶ and laboratory studies.⁶⁷ Tritium presents a different problem because most of it will generally be present in tritiated water (HTO) and will not be slowed by ion exchange phenomena.⁶⁸ Some additional work has been done on the tritium problem, but has not been published.

Underground nuclear explosions that form craters reintroduce the problem of atmospheric radioactivity. The Danny Boy Event released about 4% of the radioactivity produced,⁶⁹ with the released fraction consisting of a few tenths of a percent of the nonvolatile species and 10 to 20% of the volatiles⁷⁰ (consistent with Table I, p. 29, at early times). The fraction of radioactivity released to the atmosphere is a strong function of the depth of burial as shown in Fig. 40.⁷¹ A numerical simulation model has been developed for prediction of fallout from subsurface nuclear explosions that produce craters.⁷¹ The physical processes modeled are atmospheric transport, lateral eddy diffusion, and gravitational sedimentation of radioactive particulates. The initial conditions are based on two clouds that may be formed: the main cloud (composed mostly of vented cavity gas and particulates) and the base surge (composed of ejecta and suspended fine particulates). This model was normalized to the external gamma-dose-rate field of the Sedan (see Fig. 41) and Danny Boy cratering events.⁷¹ An electrodeless plasma system was developed⁷² to study the chemical processes which are important to fractionization of fission products during the cooling of a fireball. Processes such as condensation and interaction of fission products with molten silicates are common to both contained and cratering explosions. The particulates in the main cloud and base surge consist, to a large degree, of molten silicates. Other fallout research has been concerned with cloud sampling techniques⁷³ (see Fig. 42) and improved methods for calculating atmospheric dispersion.⁷⁴ The present state of knowledge at this Laboratory concerning the formation and ultimate distribution by atmospheric processes (excluding biological processes) of radionuclides has been summarized.⁷⁵

Related work is under way on the biological and medical effects of radionuclides introduced into the biosphere, but it is not described here because it is not a part of the Plowshare Program.

Fig. 40. Fraction of gamma activity appearing in close-in fallout pattern. (Fig. 1 of Ref. 71.)

Fig. 41. Calculated and observed gamma exposure rate at H+1 hr along the hot line of Sedan pattern (diagnostic calculation). (Fig. 6 of Ref. 71.)

Fig. 42. NATS cloud track (from a Rover reactor operation). Isopleths of counts/sec from a NaI crystal; there has been no correction for decay during time of data collection; time on this figure is for period 15-1/2 to 21-1/2 hr after cloud was produced. (Fig. 1 of Ref. 73.)

APPLICATIONS OF RESEARCH

Nuclear Physics

As noted on p.28, large quantities of excess neutrons are produced in nuclear (especially thermonuclear) explosions. These neutrons may be resolved in energy by time-of-flight measurements, and observations made of their energy-dependent interactions with matter. This technique was used in the first Plowshare experiment, Gnome, for neutron activation measurements.⁷⁶ The same technique has been used to measure the fission characteristics of U^{235} ^{77,78} and of Pu^{239} ⁷⁹.

Heavy nuclei were produced by the exposure of U^{238} to high neutron fluxes in the first terrestrial thermonuclear explosion (Mike).⁸⁰ Other high-yield thermonuclear tests have also produced heavy elements, but in lesser amounts than Mike. Part of the Plowshare Program has been concerned with the design of relatively low-yield nuclear explosives with an intense neutron flux in the region of a heavy element target. The neutron exposures achieved in these explosions are only one or two orders of magnitude smaller than those believed to be important in the stellar processes.⁸¹

The Mike Event (Fig. 43) produced nuclides with mass numbers through 255,⁸⁰ Anacostia (Fig. 44) through 246 (possibly through 254)⁸² and Par (Fig. 45)^{83,84} and Barbel (Fig. 46)⁸⁴ through 257, all with U^{238} targets. It has been postulated⁸⁰ that the Mike debris nuclides were produced by successive neutron capture in the U^{238} target to form uranium isotopes through U^{255} which then decayed by beta emission to form the observed nuclides (see Fig. 43). The Mike, Par, and Barbel results indicate a depletion of even-mass number nuclides relative to the odd-mass isotopes for mass numbers greater than 250. One proposed explanation^{83,85} involved the spontaneous fission of the even-mass nuclides during beta-decay. Another^{81,84} (see Fig. 46) assumed that heavy element production involved successive neutron capture in protactinium or neptunium as well as in uranium. Recent calculations⁸⁶ indicate that the odd-even abundances are best explained by successive neutron capture in both U^{238} and Pa^{238} , the latter formed by the $U^{238}(n,p)Pa^{238}$ reaction (see Fig. 45). A more recent experiment, Cyclamen,⁸⁷ produced a neutron exposure in a U^{238} target over 50% greater than that in Par or Barbel. No nuclides with mass numbers greater than 257 were found, although reasonable extrapolation of the Par and Barbel results would lead one to expect them. It may be that nuclides with mass numbers from 258 to perhaps 270 have half-lives short compared to sample recovery time, and that an "island" of stability could exist beyond this point. The Tweed event produced a neutron exposure similar to Par, but a Pu^{242} target was used instead of one of U^{238} . The yield curve extended only to mass number 255 and was several orders of magnitude lower than that of Par at an equal number of captures. This has been explained by assuming thermal fission competition in the plutonium capture chain.⁸⁸ These results probably indicate that higher atomic number target materials are not feasible because of their increased fissionability.

Fig. 43. Production of uranium isotopes in Mike thermonuclear Event and their decay to beta stability. $\square$ beta unstable nuclide. $\blacksquare$ beta stable nuclide. (Fig. 1 of Ref. 80.)

Fig. 44. Mass yield data, Anacostia vs Mike. (Fig. 1 of Ref. 82.)

Fig. 45. Mass-yield data for Par experiment and theoretical calculations assuming a 20-keV neutron exposure of 11 moles of neutrons/cm² and a Pa²³⁸/U²³⁸ ratio of 1.5×10^{-2} .

Fig. 46. Mass abundance vs mass number for Barbel device and theoretical calculations. Amount of uranium and neptunium exposed to the neutron flux were 10^{-1} and 10^{-4} of initial uranium respectively. (Fig. 7 of Ref. 84.)

Geophysics

Geophysicists have been "probing the earth with nuclear explosions"⁸⁹ for over two decades. The fifth nuclear explosion,¹ the underwater Baker Event at Bikini in 1946, was the first to give new geophysical knowledge. Data⁹⁰ from this explosion were used to calibrate the earthquake magnitude-energy relationship against a source of known strength. Seismic signals from the 1954 Castle series¹ at the Pacific Proving Ground that were recorded in Africa added the "final link in the chain of evidence for the existence of the earth's inner core."⁹¹ The underwater Wigwam Event (off the lower California coast in 1955¹) produced two types of surface waves that had not previously been found to propagate along oceanic paths.⁹² Data from the Baker Event, the Castle series, and the Redwing series¹ in 1956 (recorded in the United States, Australia, the Soviet Union, and other locations around the world) were used to obtain interesting results about the shear velocity in the upper mantle and the dimensions of the core.⁹³

A series of British nuclear tests in central Australia (Buffalo, 1956¹) provided the first really reliable knowledge of deep continental structure and mantle velocity in that continent.⁹⁴ The Hardtack II series (Nevada, 1958) produced extensive and accurate P-wave travel time and amplitude data across the United States.⁹⁵ The first Plowshare explosion (Gnome, New Mexico, 1961) was the first for which advance preparations, including establishing over 90 temporary recording stations, could be made (Fig. 47). Gnome gave some surprising results of particular interest because it showed striking differences in P-wave travel time and amplitudes associated with the eastern and western United States.⁹⁶ World-wide preparations were made in advance of Salmon (Mississippi, 1964) as shown in Fig. 48. Travel time results in the eastern United States were similar to those of Gnome.⁹⁷ The 5.3-kt Salmon explosion⁴ was well recorded throughout the continental United States, but only at very quiet recording stations at greater distances (see Fig. 48).⁹⁷ The larger (80-kt) Longshot explosion (Amichitka Island, 1965) was recorded by over 280 seismographic stations throughout the world, and the travel time data indicate significantly earlier arrivals than predicted, with a strong azimuthal bias in the observations.⁹⁸

Certain close-in explosion phenomena have been related to distant seismic signals. Displacement measurements near the cavity (p. 10) have been used together with reasonable earth models to calculate seismic amplitudes.⁹⁹ Underground nuclear explosions and subsequent chimney collapse (p. 20) have been used to determine that shear waves produced by both the explosion and the collapse were generated by the conversion of P-waves close to the explosion.¹⁰⁰

Many geophysical questions that may be answered with the aid of nuclear explosions have been listed.⁸⁹

Fig. 47. Map of seismograph stations receiving signals from Gnome. (Fig. 1 of Ref. 96.)

Fig. 48. Distant seismograph stations recording signals from Salmon. Smooth curve is at distance of 90° from Salmon site. Distribution of World-wide Standardized Seismograph Station (WWNSS) is also shown. (Fig. 2 of Ref. 97.)

Civil and Industrial Projects

The potential civil and industrial applications for underground nuclear explosions include (1) large-scale earth moving projects, (2) conservation, recovery, and storage of hydrocarbon resources, (3) in situ leaching or block caving of ore bodies, (4) water resource management, and (5) power generation. These engineering applications make use of the residual effects of the explosion (pp. 16 to 21) as well as cavity (and perhaps crater) formation (pp. 8 to 15). Because detailed descriptions of these applications have been published,^{2,3} they do not appear in this report. However, it is appropriate to describe the research that is required to relate the explosion effects to the application and that is used to provide technical information applicable to such specific feasibility studies as those for a sea-level canal¹⁰¹ or a natural gas reservoir stimulation project.¹⁰² Some of this work is economic as well as technical in nature. Economic studies are in order because engineering applications of Plowshare technology require both economic and technical justification. The results of such economic studies are used by this Laboratory to provide guidance in the allocation of resources among several fields of applied research.

Among the first Plowshare applications considered were water resource development and waste disposal projects involving the flow of water from craters and chimneys produced by nuclear explosions. Scale model studies have been made in the laboratory to determine the hydraulics of nonsteady flow from large-diameter wells (chimneys) into unsaturated confined formations,¹⁰³ similar flow from surface cavities (craters),¹⁰⁴ and from cavities (chimneys) into unconfined aquifers.¹⁰⁵ These experiments were supplemented with economic studies^{106,107} of ground water recharge projects which may employ nuclear explosives as well as more conventional construction methods. It is concluded¹⁰⁶ that nuclear construction techniques are economically competitive for large projects. A computer code developed to calculate nonsteady underground water flow¹⁰⁸ was successfully adapted and applied¹⁰⁹ to the nonsteady hydraulic phenomena modeled in tests.^{103,105} These applications await resolution of the radioactivity problem with respect to biological effects (particularly that of tritium, see pp. 28-31), and situations where the use of nuclear explosives is economically desirable.

One application where the radioactivity problem is believed to be minimal is that of in situ copper leaching. Experiments have been conducted with various granite specimens including some from the Hardhat chimney.^{12,29,43} It has been found that the rubble produced by this nuclear explosion had more microfractures than other kinds of samples; e.g., from outside the chimney, or quarried or cored from locations not subjected to the explosion (see Figs. 49 and 50).¹¹⁰ If copper ore bodies respond to explosions in the same manner, these are encouraging results.

Fig. 49. Photograph of granite specimen from Hardhat chimney in ultraviolet light. Specimen was subjected to standard commercial copper leaching solution to which a water-soluble dye (Zyglo-22) was added. (Fig. 1 of Ref. 110.)

Fig. 50. Photograph (in ultraviolet light) of sample of shaft-mined granite treated in same manner as specimen in Fig. 49. Note difference in leach solution penetration indicated by dye. (Fig. 3 pf Ref. 110.)

Because of considerable interest in the application of nuclear explosives to the petroleum industry, related studies have been and are being made. One example is the simplified analysis of some aspects of natural gas well stimulation including productivity, energy-deposition, and radioactivity scaling effects as a function of explosive size.¹¹¹ An economic analysis of using nuclear explosives to construct natural gas storage facilities has been completed, and economic trade-offs involving yield and depth of burial are indicated.¹¹² The Salmon cavity⁴ and Handcar chimney⁴⁴ pressurization tests are significant preliminaries to a natural gas storage experiment. The oil shale deposits in the western part of the United States are among the largest potential sources of petroleum in the world. One promising technique for recovering oil from these shale deposits is that of retorting the shale in a chimney formed by a nuclear explosion.³ A statistical technique⁴⁸ has been applied to the problem of oil shale chimney rubble size distribution.¹¹³ Small-scale experiments (relative to the scale of a nuclear explosion-produced chimney) have been conducted by the U.S. Bureau of Mines that are pertinent to the in situ retorting of shale in the chimney.¹¹⁴ Some results of these promising experiments are shown in Figs. 51 and 52.

Other "applications-oriented" research is under way, but published results are not yet available. Two new computer codes are being used to study problems associated with underground engineering. One code, which is operational, computes perfect gas flow in one dimension (planar, cylindrical or spherical geometry) through a porous medium (darcy or nondarcy flow) for a variety of thermodynamic processes (adiabatic, isothermal, or local temperature equilibrium with the porous heat-conducting medium). This code is being applied to such problems as natural gas well performance and a first approximation to one aspect of the problem of stemming underground explosions. The other code, which is in an advanced state of development, computes two-phase (oil and gas) darcy flow through a porous medium in a two-dimensional, cylindrical coordinate system, and is obviously directed toward analysis of natural gas wells. The purging of radioactivity from chimneys, studied briefly,¹¹¹ is receiving further attention.

Fig. 51. Typical retort bed temperatures during retorting. Air flow and burning front moved from top to bottom of retort. (Fig. 5 of Ref. 114.)

Fig. 52. Temperature profile through block of oil shale during retorting. (Fig. 6 of Ref. 114.)

ACKNOWLEDGMENTS

This report was written at the request of Glenn C. Werth, Associate Director of the Lawrence Radiation Laboratory, and I appreciate the challenge and enjoyment of writing it.

The following Laboratory colleagues gave me invaluable assistance during the preparation of this report by offering suggestions for subject matter, answering many technical questions, and making constructive criticisms of the preliminary draft:

C. R. Boardman, T. R. Butkovich, J. T. Cherry, T. V. Crawford, D. W. Dorn, A. L. Edwards, J. R. Hearst, R. A. Heckman, G. H. Higgins, F. Holzer, J. S. Ingley, J. S. Kahn, J. B. Knox, O. H. Krikorian, J. A. Miskel, D. N. Montan, W. E. Nervik, M. D. Nordyke, D. E. Rawson, D. L. Springer, D. R. Stephens, P. C. Stevenson, R. W. Taylor, H. A. Tewes, and G. C. Werth.

The efforts of the Technical Information Division of this Laboratory in preparing this report for publication are also appreciated.

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