Nuclear Excavation Technology

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Large-scale excavation is perhaps the most obvious and straightforward use of nuclear explosives. The size of the excavation depends on several factors, such as the explosive yield, medium, and depth of burst. Considerable knowledge has been obtained over the last several years on the cratering effect of chemical and nuclear explosives in a variety of media. Further, it has been shown that several explosives, spaced approximately a single-crater radius apart and detonated simultaneously, will produce a uniform channel with a width and depth about equal to single-crater dimensions. Such a channel may be used for applications such as waterways and railroad and highway cuts.

Burial of the nuclear explosive at such a depth that almost maximum dimensions are obtained results in trapping more than 90 percent of the radioactivity underground. This entrapment, when combined with the use of nuclear explosives in which a very small fraction of the energy comes from fission processes, allows nuclear excavation to be used in remote areas with complete radiological safety.

Presently published costs for nuclear excavation indicate that the unit cost of excavation decreases with increasing depth of excavation. In general, nuclear excavation is economical for depths greater than 100 ft. It is anticipated that future technological development and mass production of nuclear explosives will substantially reduce present published device costs.

•NUCLEAR EXCAVATION is the name given to the concept of using large-scale nuclear explosion craters for useful projects, such as harbors, canals, and roadway cuts. It is one of the principal applications of the Plowshare Program for industrial, or peaceful, uses of nuclear explosives. Plowshare is sponsored by the U. S. Atomic Energy Commission and is under the technical direction of the Lawrence Radiation Laboratory at Livermore, California. At the present time studies relating to the use of nuclear explosives for excavation, power generation, mining, salt water conversion, and isotope production are in progress. Of these, excavation is the most straightforward and nearest to practical application.

The purpose of this paper is to describe cratering concepts and the present state of nuclear excavation technology. The general nature of the safety hazards associated with nuclear excavation is also discussed. Specific application of these techniques to large-scale construction and engineering projects is discussed in the following papers.

CRATERING

Conventional excavation methods in hard rock require that the material first be shattered by chemical explosives and then excavated by mechanical means. In nuclear

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excavation, the force of the explosion itself is used not only to shatter the rock but also to accomplish the removal of material.

The crater dimensions depend on the energy of the explosions, the depth of burial of the explosive, and the properties of the medium. Figure 1 shows cross sections of craters formed by an explosion at progressively deeper depths of burst. To better understand the effect of varying depth of burst and medium properties it is proper to discuss the mechanisms involved in the cratering process.

One phenomenon present in all underground explosions to varying degrees, whether they be chemical or nuclear explosions, is the crushing, compaction, and plastic deformation of the medium immediately surrounding the source of the explosion. As the high-pressure gases generated by the explosion push on the walls of the cavity, a shock wave is generated that is characterized by a spherical surface across which there is a sharp discontinuity in the physical state of the material. This discontinuity propagates outward at a velocity which, for high pressures, is faster than the speed of sound in the medium. For chemical explosives the initial pressures are of the order

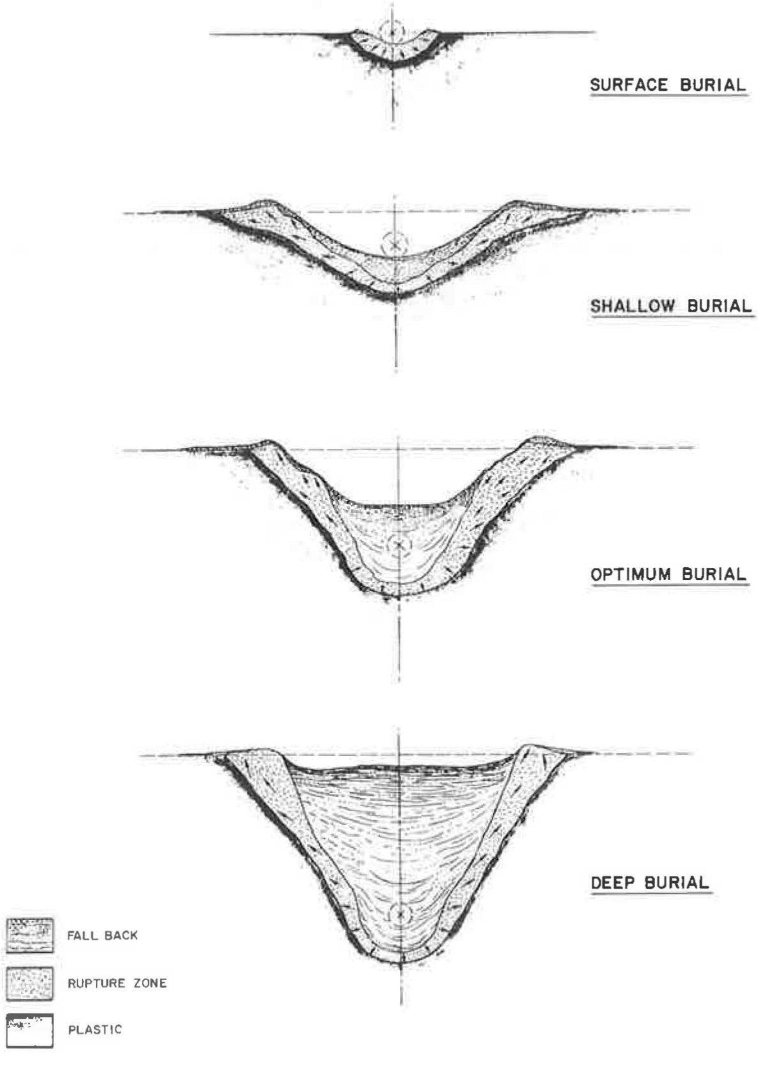

Figure 1. Typical crater profiles vs depth of burst for alluvium.

of 100,000 to 200,000 atm; for nuclear explosives they are as large as 10 to 100 million atm, depending on the initial cavity size. For nuclear explosions the medium initially is melted and vaporized as the shock passes through it. As the shock wave moves outward in a spherically diverging shell, the medium behind the shock front is put in radial compression and tangential tension, resulting in radial cracks directed outward from the cavity. The peak pressure in the shock front drops because of spherical divergence, as well as energy expenditure in doing work on the medium. For shock pressures greater than the dynamic crushing strength of the material, this work appears in the form of crushing, heating, and physical displacement. In regions outside this limit the shock wave will still produce permanent deformation by plastic flow until the peak pressure in the shock front has decreased to a value equal to the plastic limit for the medium. This plastic limit marks the boundary between the elastic and plastic zones (Fig. 1). The limits of crushing and plastic deformation vary widely from material to material.

This picture of the first few milliseconds of an explosion neglects the effects of any free surface, effects which are exceedingly important. As a compressive wave encounters a free surface, it must match the boundary condition that the pressure—or, more correctly, the normal stress—be zero at all times. This results in the generation of a negative stress wave or rarefaction which propagates back into the medium. The medium breaks in tension under the action of this rarefaction, and the broken pieces fly upward with a velocity characteristic of the total momentum trapped in it. For a loose material like alluvium, this process, called "spall," makes almost every particle fly into the air individually, whereas in a rock such as basalt the thickness of the slabs is generally determined by presence of pre-existing joints and zones of weakness. As the distance from the explosion to a point on the free surface increases, the peak pressure decreases, and so the maximum possible tensile stress decreases until it no longer exceeds the tensile strength of the medium. In addition, the velocity given to the spall decreases in proportion to the decrease in peak pressure.

For ranges beyond the point where spall occurs, the negative stress in the rarefaction wave will decrease the shear strength of the medium, resulting in large plastic deformations and ruptures. This makes the rupture zone extend a considerable distance along the surface and contributes to the formation at the lip. Ultimately, the surface expression of a deep underground explosion is only a small elastic excursion of the surface.

Another mechanism of importance in cratering, particularly for deeper craters, is termed "gas acceleration." This is a long-period acceleration given the material above the explosion by the adiabatic expansion of the gases trapped in the cavity. For some cases, particularly for deep depths of burst, this gas also gives appreciable acceleration during its escape through cracks extending from the cavity to the surface. For very shallow depths of burst the spall velocities are so high that the gases are unable to exert any pressure before venting occurs. For very deep explosions, the acceleration given the overlying material is negligible.

Subsidence is the fourth major process that makes a significant contribution to the formation of the apparent crater. It is very closely linked to the first process of compaction and plastic deformation, without which there would be no void into which material could subside. Subsidence occurs when the spall or gas acceleration has so distended the overlying material that large cracks are produced through which the explosion gases escape. The overlying material, having been fractured and crushed by the shock wave, collapses into the cavity. Subsidence is most important, of course, for very deep explosions, because if the density of the subsidence material is not significantly different from its pre-shot density, all cavity volume may be transmitted to the surface and result in the formation of a surface crater.

Effects of Depth of Burst, Yield and Material

For a given material, crater size is a function of yield, as well as of depth of burst. Dimensional analysis suggests that crater dimensions should be proportional to the $1/3$ power of the explosive yield. Experimental results to date indicate that

$^{1}/_{3.4}$-power scaling is more accurate for predicting apparent crater dimensions at large yields. Because apparent craters are of primary interest in nuclear excavation, $^{1}/_{3.4}$ is used as the scaling exponent.

For detonation of a given yield, the size of the crater formed varies greatly with the depth of burial (DOB) of the charge. As DOB increases, crater dimensions increase to a maximum at some optimum depth, then decrease until a depth of burst is reached where no crater is formed. Figure 2 shows the relationship between the radius and depth of the apparent crater and depth of burst for the alluvium of the Nevada Test Site. The curves were fitted to the high explosive data by the method of least squares using $W^{1/3.4}$ scaling, in which W is the energy release in kilotons, a kiloton (kt) being an energy release equivalent to 1,000 tons of TNT or, more precisely, 10^{12} cal.

Using the empirical scaling law, cratering explosions at different yields can be correlated to establish the relationship between crater dimensions and depth of burst. This is done by reducing all distances associated with a yield, W, to those applicable to 1 kt by dividing the depth of burst and dimensions by $W^{1/3.4}$. Figures 3 and 4 show the crater radius and depth data for desert alluvium scaled to 1 kt by this law.

Of particular interest is the data point from the Sedan event, a 100-kt cratering experiment in alluvium. Figure 5 shows the Sedan crater in relation to construction equipment in the foreground and to a number of other high-explosive and nuclear craters in Area 10 at the Nevada Test Site in the background. The data point for crater depth from Sedan appears to fall almost exactly on the curve. The data point for crater radius falls about 15 percent below the curve.

Also shown in Figures 3 and 4 is the general area in which data from very deeply buried large-yield (1 to 100 kt) nuclear explosions fall. These are craters formed by

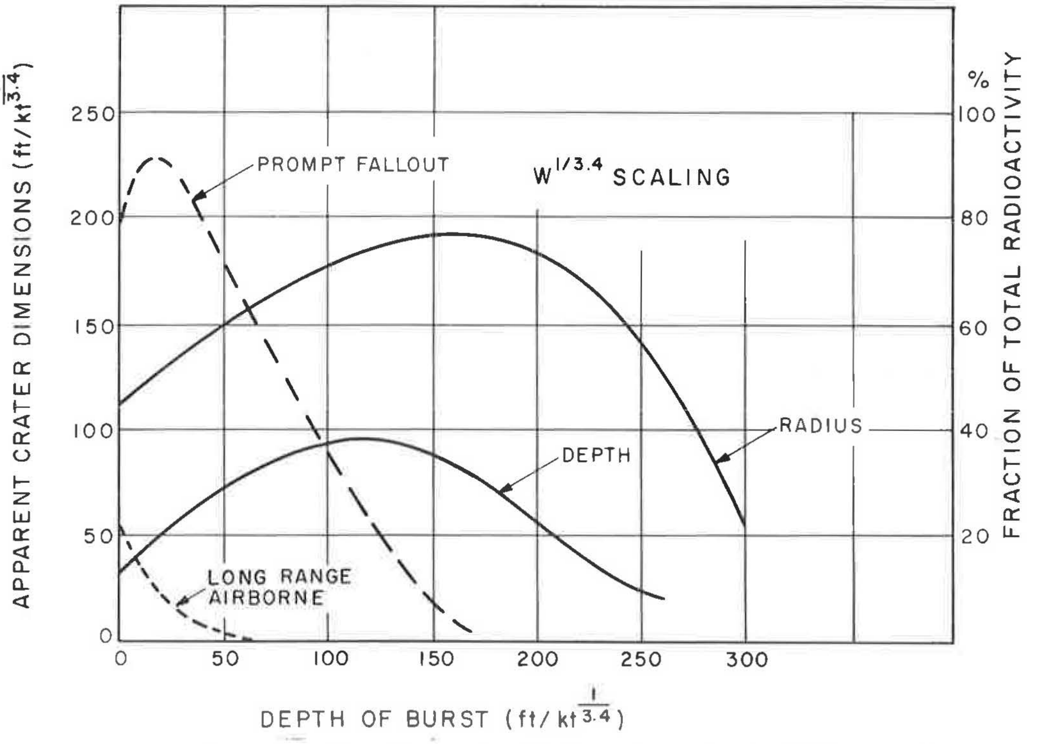

Figure 2. Apparent crater dimensions and activity release vs depth of burst in desert alluvium (for 1-kt explosion).

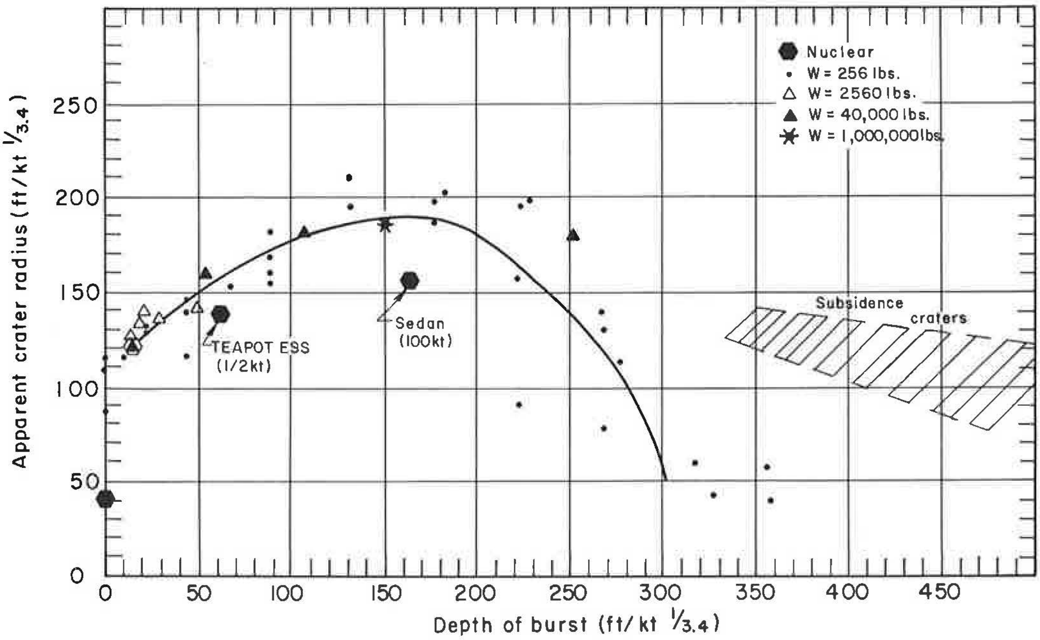

Figure 3. Apparent crater radius vs depth of burst in alluvium.

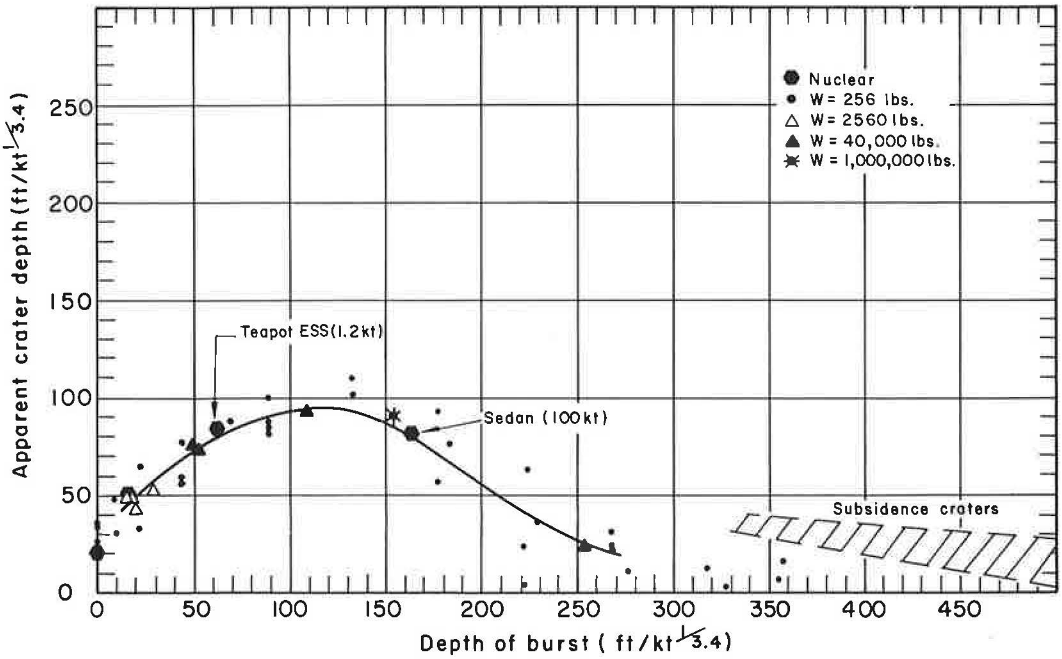

Figure 4. Apparent crater depth vs depth of burst in alluvium.

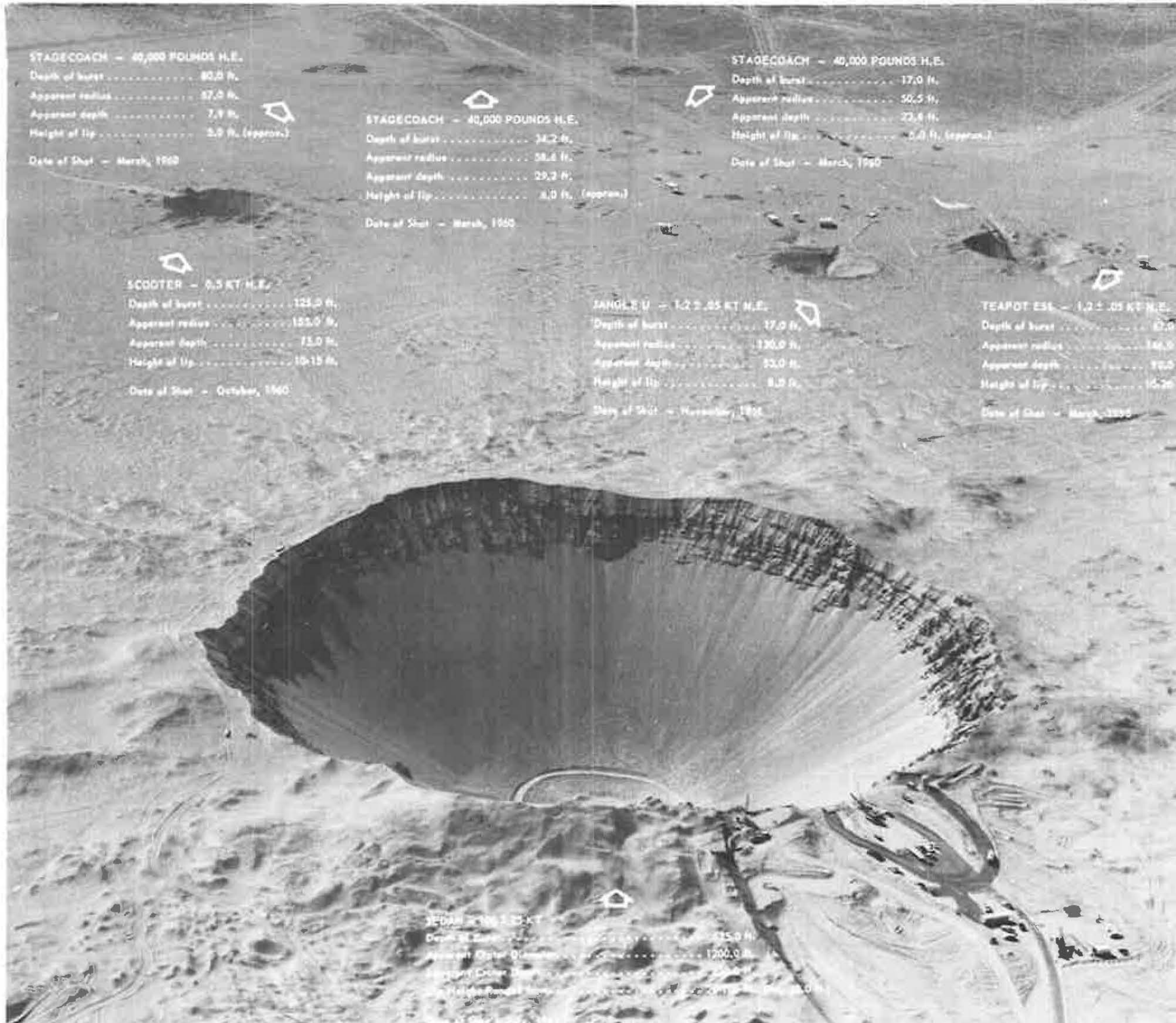

Figure 5. Sedan crater, 100-kt cratering experiment, shown in relation to other high explosive and nuclear craters.

collapse of material into the initial explosion cavity and subsequent formation of a subsidence to the surface. These data, together with Sedan, indicate that the depth-of-burst curve for the radius of nuclear craters peaks approximately 15 percent below the curve for high explosive craters, whereas the curve for depth of nuclear craters is approximately the same.

Figures 6 and 7 show cratering curves for basalt and the data from which they were drawn. The only nuclear cratering detonation in basalt is Danny Boy, a 0.42-kt experiment at a depth of burst of 110 ft. The Danny Boy crater is 107 ft in radius and 62 ft deep (Fig. 8). The scale of the crater and the size of the fallback debris may be judged from the size of the pickup truck.

The large amount of scatter in the chemical explosive data in basalt is due primarily to the small yields used for most of the shots. Indications are that reliable results in a hard rock are achieved only when the yields are large enough to produce craters with dimensions many times larger than the average block size of the crater debris. In recognition of this problem, the available data were weighted by a process based on the average debris size relative to the crater size. The basalt curves were then determined using the weighted data and standard regression analysis.

The scaled depth of the crater made by the one nuclear shot in basalt falls very near the depth curve, but the scaled radius falls about 10 percent below the radius curve. The difference is not as great as noted in alluvium, but the results tend to confirm the indication that nuclear craters have smaller radii than craters made by chemical explosions of the same yield.

Applicable cratering experience in other types of hard, dense, competent rock is very limited. A study of the cratering mechanisms and the material properties that affect cratering leads to the conclusion that the cratering curves for most of these rocks should be very similar to those for basalt.

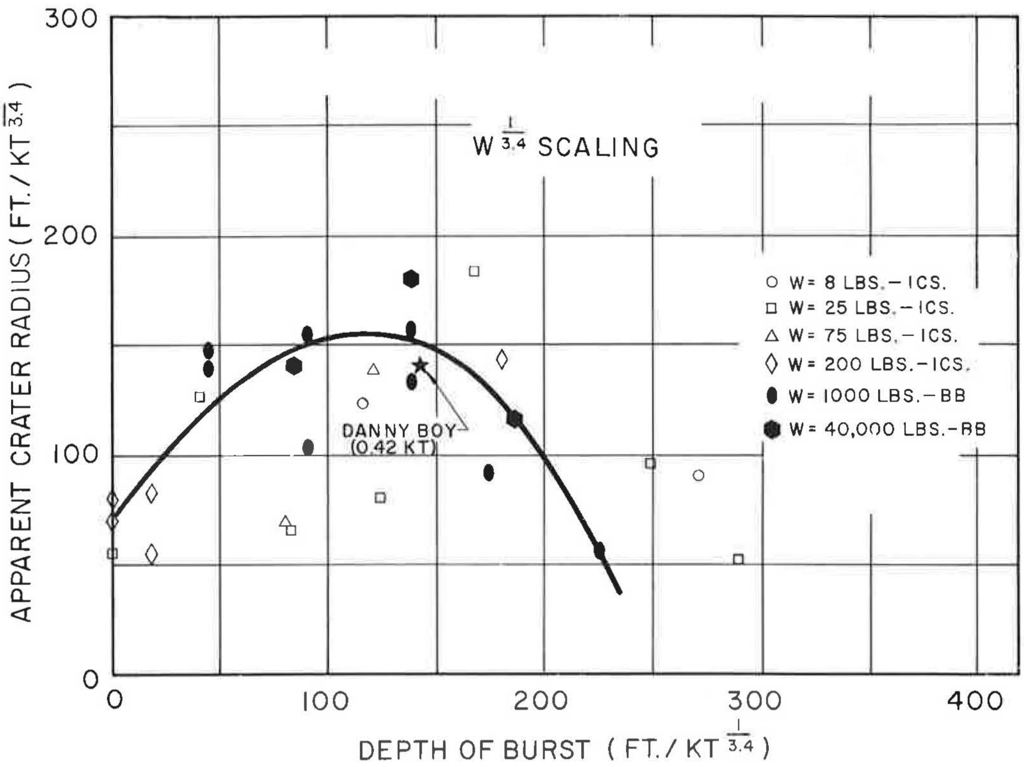

Figure 6. Apparent crater radius vs depth of burst in basalt.

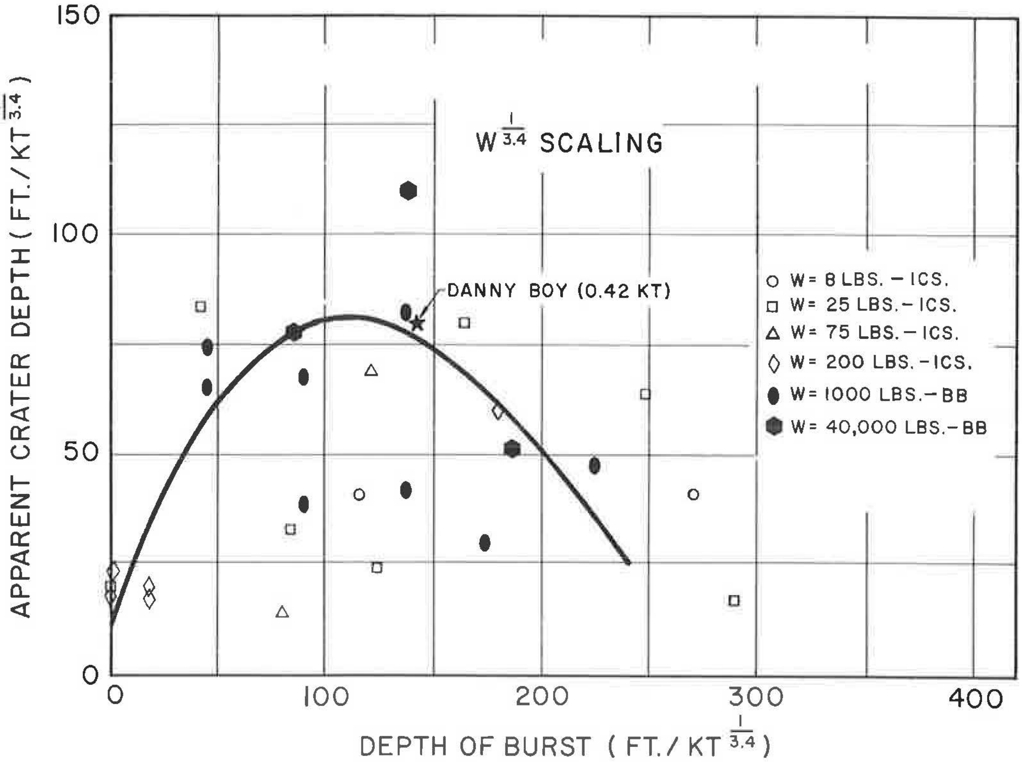

Figure 7. Apparent crater depth vs depth of burst in basalt.

Row Charges

High-explosive cratering experiments in alluvium have shown that a row of explosions, properly spaced and detonated simultaneously, will produce a series of interconnected craters forming a channel. This channel will be roughly parabolic in cross section with dimensions and smoothness that depend on the spacing of the charges. In comparing row charges with single-crater detonations, there are two significant modifications to the lip pattern: (a) the crater lip is appreciably higher in the case of row charges; and (b) there is no significant lip at the ends of the ditch. Figure 9 shows a row crater that demonstrates these effects.

For a given depth of burst, the charge spacing has a significant effect on the dimensions of the cut. Based on experience in alluvium, spacing charges at a distance of 1.0 single-charge crater radius results in a cut with a depth and width 10 to 20 percent greater than the depth and diameter of a single-charge crater. Increasing the spacing to 1.25 single-charge crater radius results in a cut with about the same width and depth as a single-charge crater. A further increase to 1.50 radius spacing results in a cut which is quite irregular and has a width about 10 percent less and a depth 50 percent less than the corresponding single-charge crater dimensions. There is no applicable experience available on row-charge effects in rock, but it seems reasonable to assume that the same general effects would be seen.

RADIOACTIVITY

Effect of Depth of Burst

The radioactivity generated in deep cratering explosions is distributed primarily in two ways:

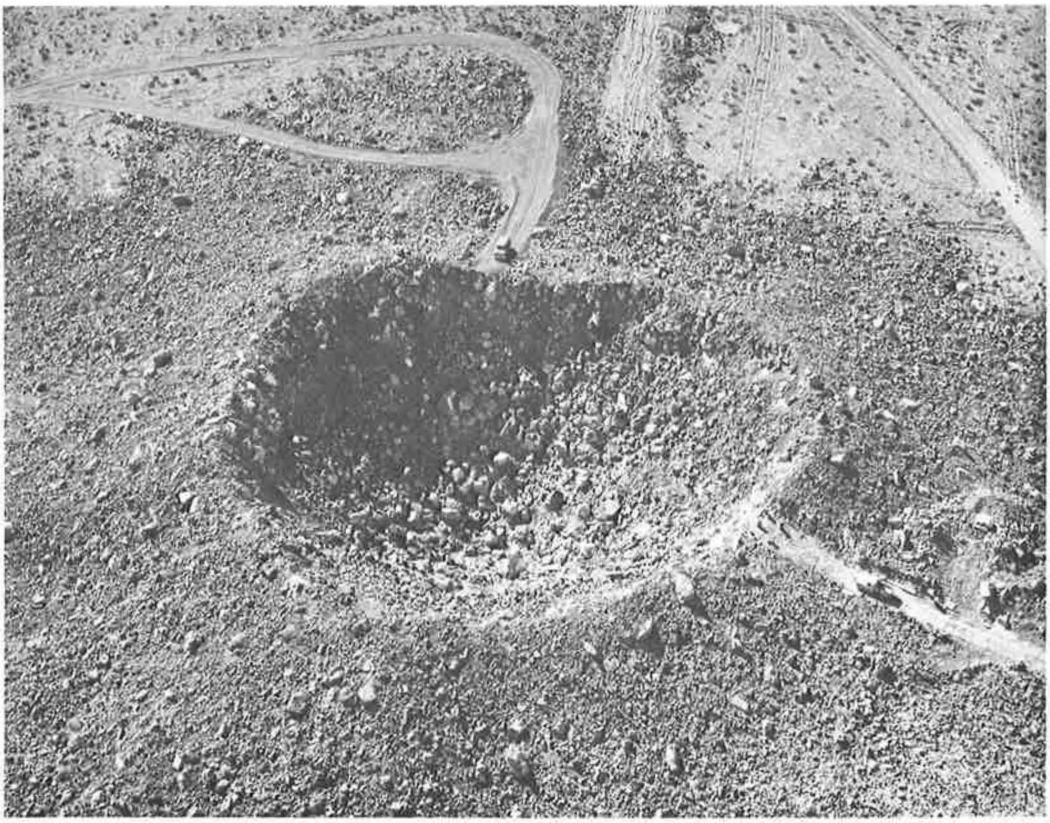

Figure 8. Danny Boy crater, 0.42-kt cratering experiment in basalt.

Figure 9. End view of Pre-Buggy I crater, produced by the simultaneous detonation of five 1,000-lb high explosives, showing small lips at ends of ditch.

1. Most of the activity is trapped by particles of debris which end up buried in the rubble and fallback in the crater or on the lip.
2. A much smaller fraction, including those products which are gaseous at early times, escapes to the surface and is scavenged by the particles in the dust cloud and deposited as "prompt" fallout. More than 90 percent of this prompt fallout falls within 5 mi of the detonation.

The contribution to "world-wide" fallout by gas or solids carried by minute particles is virtually zero for deeply buried cratering detonations.

The amount of activity that escapes and is deposited as prompt fallout depends mainly on how deep the explosive is buried compared to the depth of the resulting crater. Figure 2 shows the relationship for desert alluvium between the scaled depth of burst, the scaled crater dimensions, and the amount of radioactivity released to the atmosphere. As DOB increases, the prompt fallout continues to decrease and ultimately reaches a point of complete containment.

The depth curve in Figure 2 shows that the depth of burst which gives the greatest crater depth occurs at a point at which about 25 percent of the activity is released. The radius curve shows that the scaled DOB at which the maximum radius is achieved corresponds to a point on the prompt fallout curve at which about 2 percent of the activity is released.

The decrease in radioactivity escape with increasing burial depth is an important factor in nuclear excavation projects. The general form of the curve is the same in all materials, but the percentages of containment vary with materials. For the Danny Boy detonation, the escape fraction was measured at 4 percent; for Sedan, it was about 10 percent.

No rows of nuclear charges have been fired to date; therefore, data are lacking on radioactivity escape from such multiple-charge detonations. Small-scale cratering studies using radioactive tracers have indicated that the escape fraction from single- and multiple-charge detonations having the same ratio of depth of burst to depth of crater are equal.

Types of Radioactivity

The radioactivity resulting from a nuclear explosion can be placed in two classes according to primary origin. One class includes the fission products created by the detonation. The other includes nuclides produced by interaction between neutrons from the thermonuclear reaction in the device and the soil or rock surrounding the device. Continuing research is under way to reduce the amount of fission activity associated with nuclear explosions at all yields to a level well below present experience. The use of neutron-absorbing materials around the explosive can reduce the soil or rock activation to an insignificant level.

Both fission-product and neutron-induced activity are composed of two types of nuclides. The first are those nuclides which emit high-energy gamma rays and constitute an external hazard to the body in the form of whole-body irradiation. The other is the internal hazard associated with radionuclides which may be ingested, assimilated, concentrated, and retained in vital organs of the body. Consequently, the reduction of the amount of radioactivity produced and the containment of that which is unavoidably manufactured are objectives in all nuclear excavation projects. Current studies have shown that both types of radioactivity can be controlled and excavation projects in remote areas can be carried out with no significant radiological hazard.

AIR BLAST

Nuclear detonations can cause air blast damage close to the detonation by the direct blast wave, at intermediate ranges by refraction or "ducting" of the blast wave in the troposphere below 50,000 ft altitude, and at long ranges by refraction in the ozonosphere at 100,000 to 150,000 ft altitude. To control this potential hazard, it is necessary to understand the air blast signal produced by nuclear cratering detonations, the transmission of air blast under various weather conditions, and the response of the typical structures in incident blast waves.

Experience has shown that there is a 50 percent probability of damage to large plate-glass windows if the air blast peak overpressure is about 3 mbars, to average-size windows if it is about 4.5 mbars, and to average wood doors if it is about 13 mbars. A safety criterion of 2 mbars has been used for inhabited areas where replacement values would be unacceptably high. In a remote, sparsely populated area a limit of 10 mbars is considered to be reasonable.

Close-In Blast

The distance at which the direct blast wave produces a given peak overpressure scales as the $1/3$ power of the explosive yield and is fairly independent of wind and weather within approximately 5 mi. Beyond this distance, refraction effects predominate and meteorological conditions determine the blast overpressure.

Intermediate-Range Blast

Troposphere refraction of the blast wave back toward the ground at ranges of 30 to 100 mi results from a layer of air in the troposphere with a higher sound velocity than that at the surface. This layer is usually associated with the presence of jet stream winds. Generally, in any period of a few weeks there would be many days of favorable weather when there would be a negligible chance of damaging overpressures from tropospheric refraction. Therefore, the air blast hazard at intermediate ranges is primarily an operational, rather than a design, problem.

Long-Range Blast

Long-range blast peak overpressures are experienced in a "caustic range," 80 to 150 mi from the detonation in one direction, and depend strongly on the ozonospheric weather conditions. Winds at this altitude vary seasonally, generally blowing from the east in summer and from the west in winter in the Northern Hemisphere. The long-range blast overpressure may vary as much as a factor of 10 from the most favorable to the worst times of the year, corresponding to the times when the point is upwind or downwind of the detonation, respectively. Day-to-day variations in the ozonospheric winds cause considerable variability in the magnitude of the blast pressures experienced at any point downwind in the sound ring. These variations, as well as the seasonal variations, are predictable once the local weather patterns are well established. Measurements indicate that under identical weather conditions the overpressure at caustic ranges scales as the 0.4 power of the explosive yield.

Blast Attenuation

The air blast from an underground explosion is attenuated significantly more than that from a surface explosion. Generally, burial reduces close-in air blast by a factor of 10 to 100. Long-range air blast is attenuated by a factor between 3 and 10 by burial. The attenuation increases with scaled depth of burst, but large variations from one medium to another and between nuclear and chemical explosives have been experienced.

GROUND SHOCK

Large-yield nuclear detonations may cause damage to structures and other cultural features by inducing ground motion where structures are located. In general, the intensity of ground shock is dependent on the yield of the detonations, the distance to vulnerable works, the geology of the area, and the types of structures involved.

The ground shock produced by a nuclear explosion generates seismic waves which travel many miles with potentially damaging intensities. The nature of the material surrounding the detonation and the degree of its coupling of the shot greatly affect the amount of energy available for transmission through the earth. For example, the energy transmitted as ground shock from detonations in granite, basalt and other hard rocks may be as much as 10 times greater than those in alluvium. Contained shots produce ground shock about a factor of 2 greater than cratering detonations at optimum depth due to more efficient coupling.

Transmission of the seismic waves between the shot point and structures of interest is dependent on the geology through which the waves must travel, the types of materials, bedding planes, and discontinuities.

The type of material on which a structure is located and the nature of the structure itself have a significant effect on the damage which may be sustained. Much higher accelerations and displacements are observed at the surface of deep alluvial deposits than in rock. The design and construction of structures determine their response to the accelerations, displacements and frequencies of the ground motion.

It is difficult to specify damage criteria in terms of a single parameter of ground motion, because damage is dependent on the peak acceleration at a point, the associated displacement, and the duration of the ground motion. Two sets of criteria have been used in construction and quarry blasting—one based on acceleration, the other on velocity. These criteria were developed empirically through vibration tests and experience. Of the two criteria, velocity would appear to be a better basis for establishing safety limits because the data for velocity are based on actual blasting tests and are more conclusive. By instrumenting buildings during construction blasting, it has been found that a peak surface velocity of 12 cm/sec represents a level at which the probability of damage is small. At a velocity of 8 cm/sec there appears to be less than 1 percent probability of damage such as cracking of plaster in residential buildings. For peak surface velocities greater than about 40 to 80 cm/sec, there is an appreciable probability of frame damage to residential-type structures.

CONCLUSIONS

This summarizes the present state of the art in nuclear excavation technology. Considerable data have been obtained over the last 10 yr on the effects of nuclear and chemical cratering explosions. These data have indicated the capabilities and limitations of nuclear explosives. It is concluded that nuclear explosions are capable of making craters suitable for many large-scale construction projects and that, with appropriate safeguards and studies, they can be used safely.