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5 Reports

Special Committee on Nuclear Principles and Applications

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Contents

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

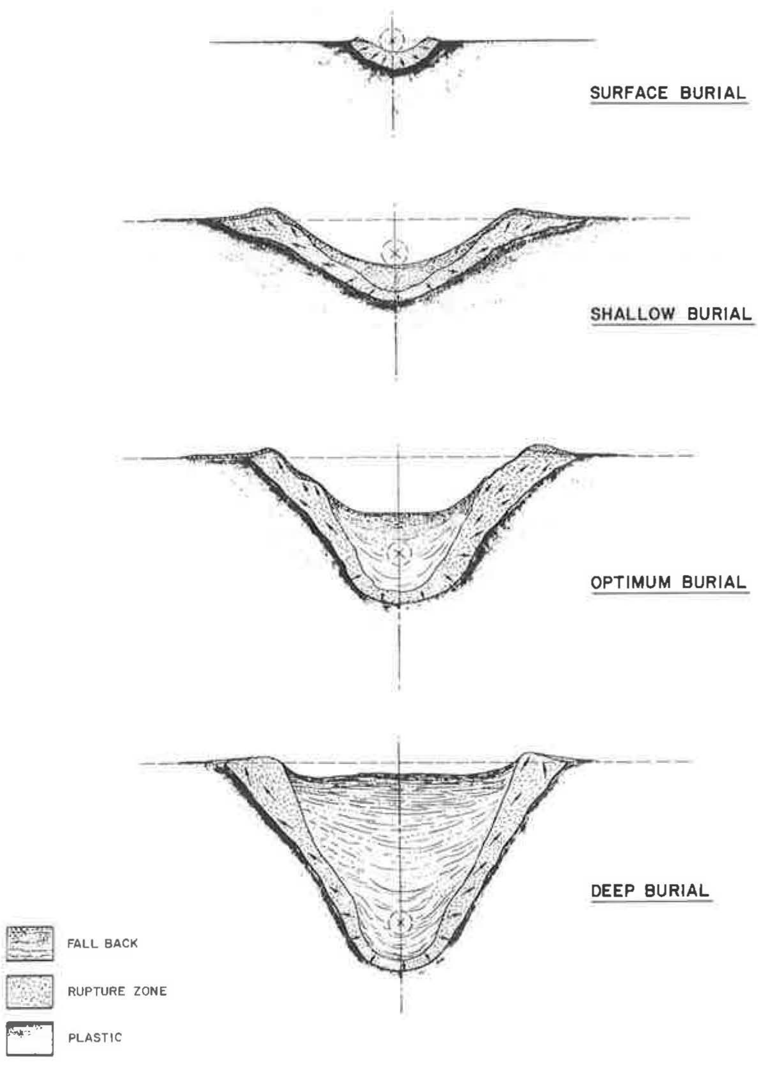

Figure 1. Typical crater profiles vs depth of burst for alluvium.

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 $\frac{1}{3}$ 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

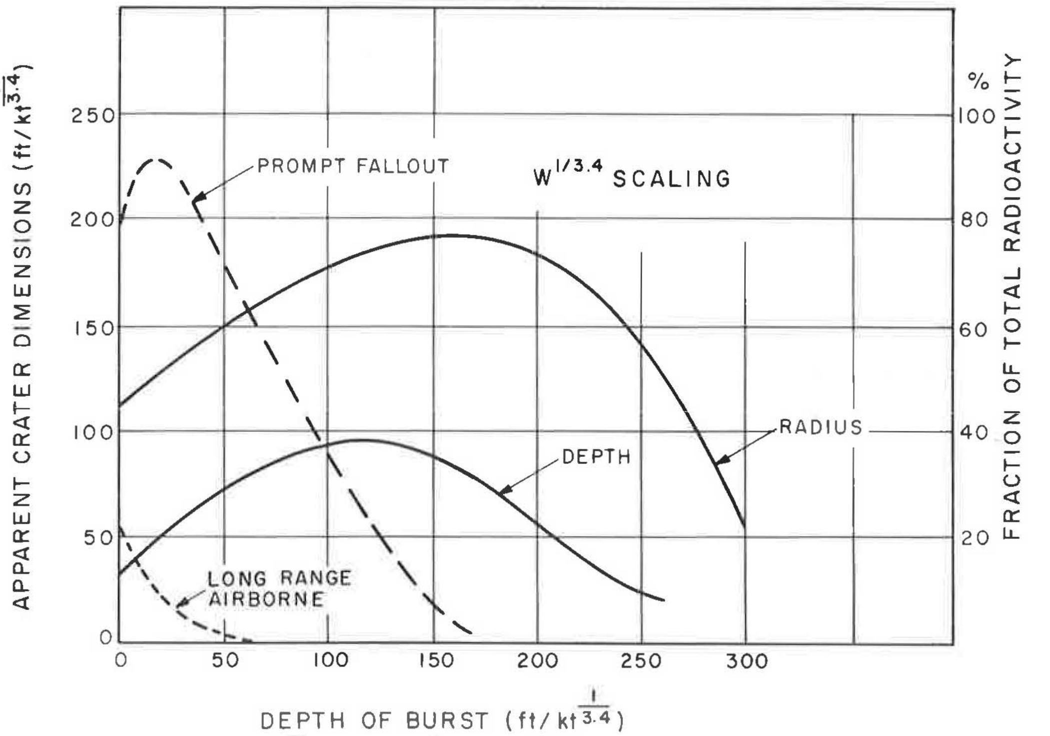

Figure 2. Apparent crater dimensions and activity release vs depth of burst in desert alluvium (for 1-kt explosion).

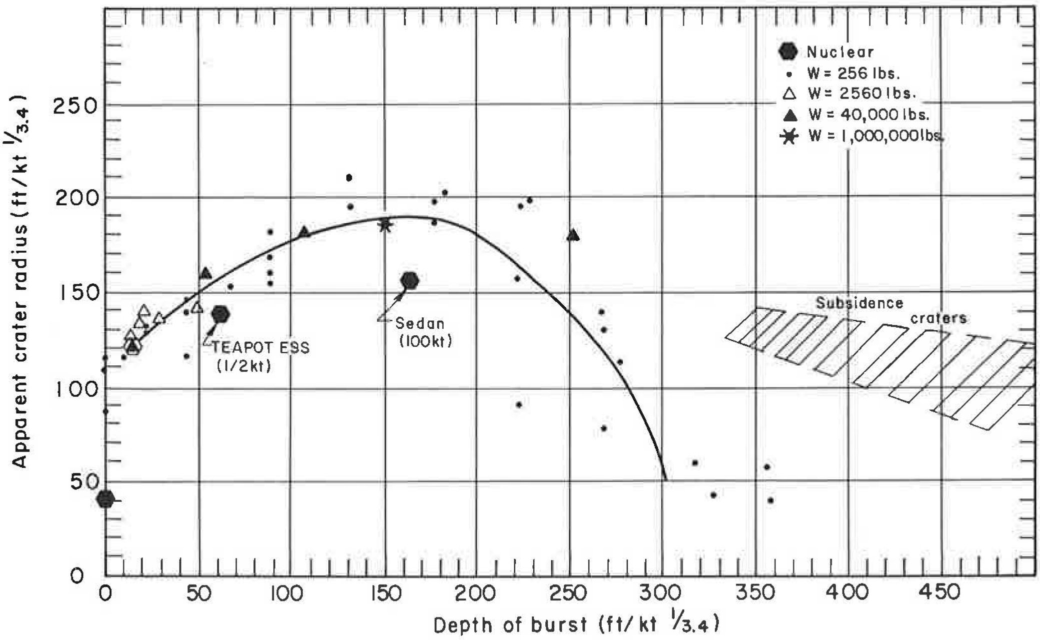

Figure 3. Apparent crater radius vs depth of burst in alluvium.

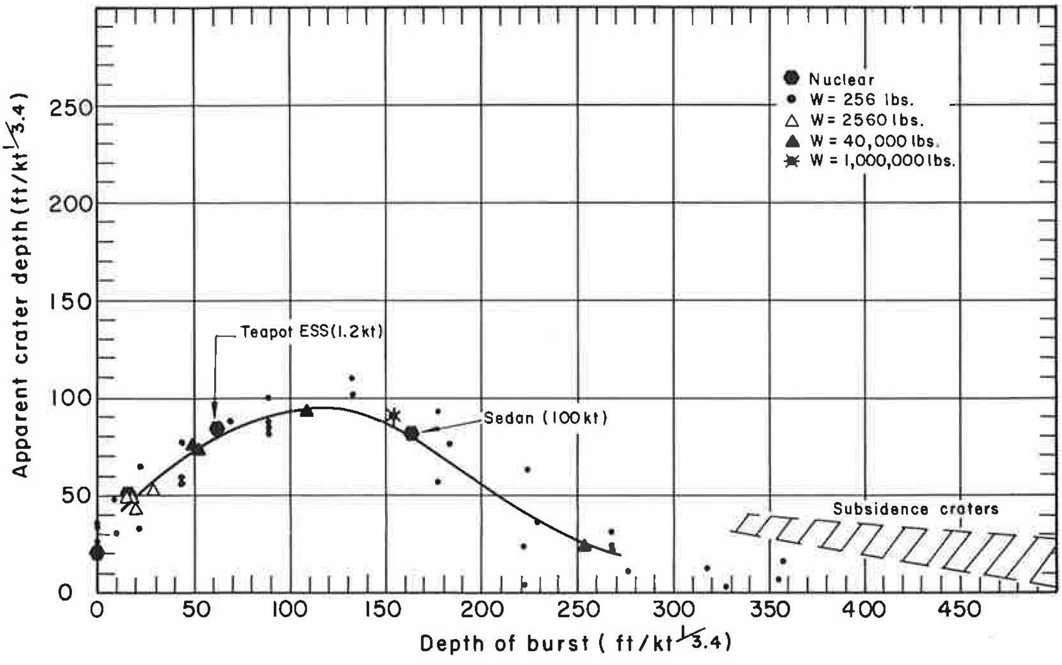

Figure 4. Apparent crater depth vs depth of burst in alluvium.

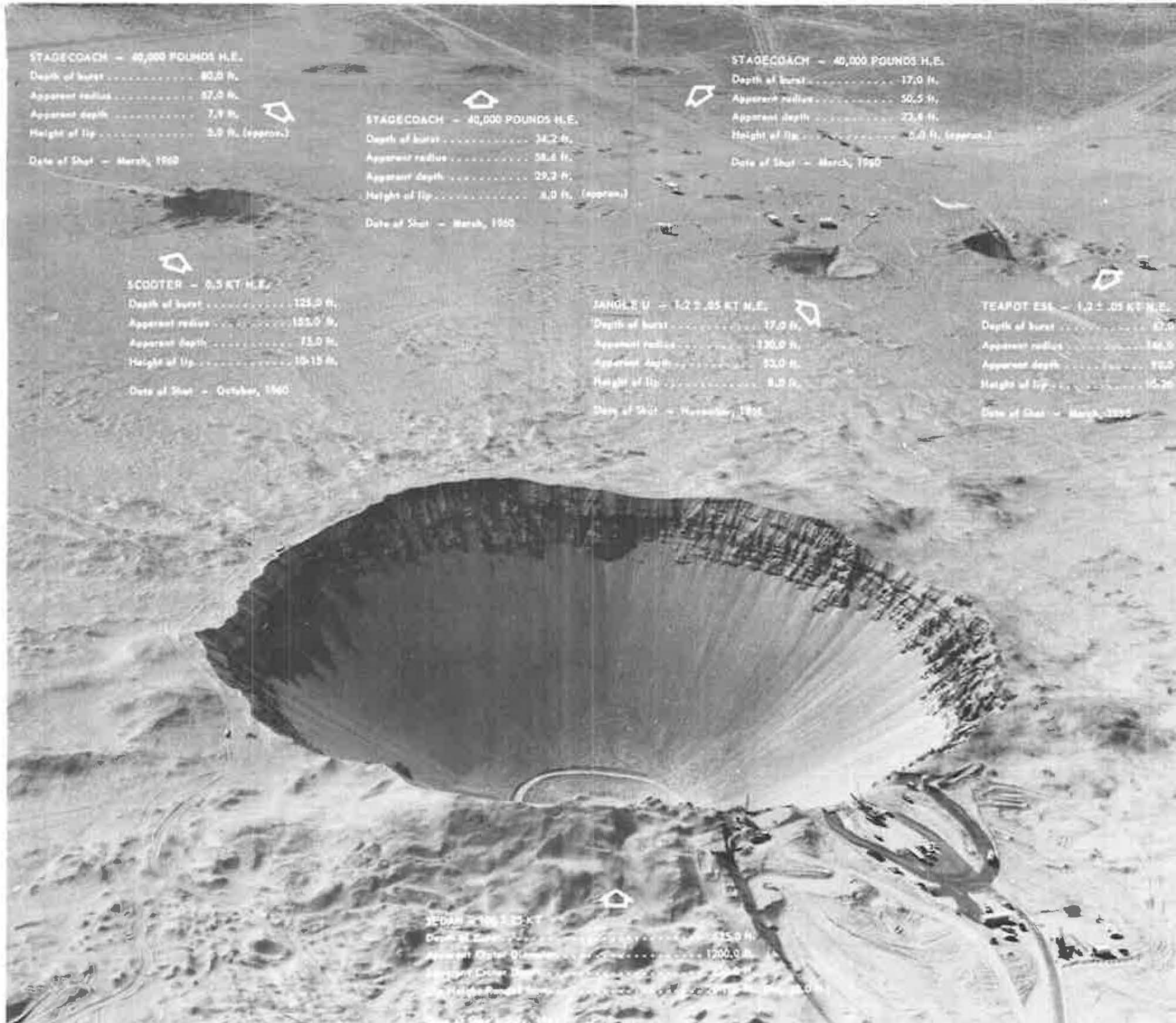

Figure 5. Sedan crater, 100-kt cratering experiment, shown in relation to other high explosive and nuclear craters.

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.

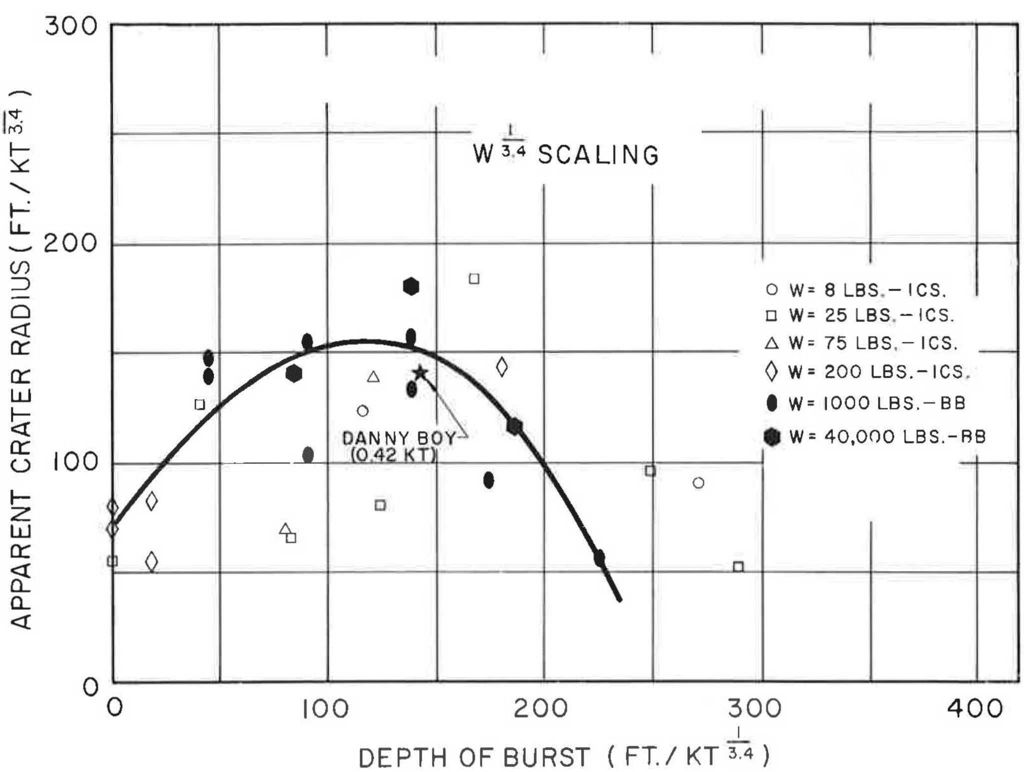

Figure 6. Apparent crater radius vs depth of burst in basalt.

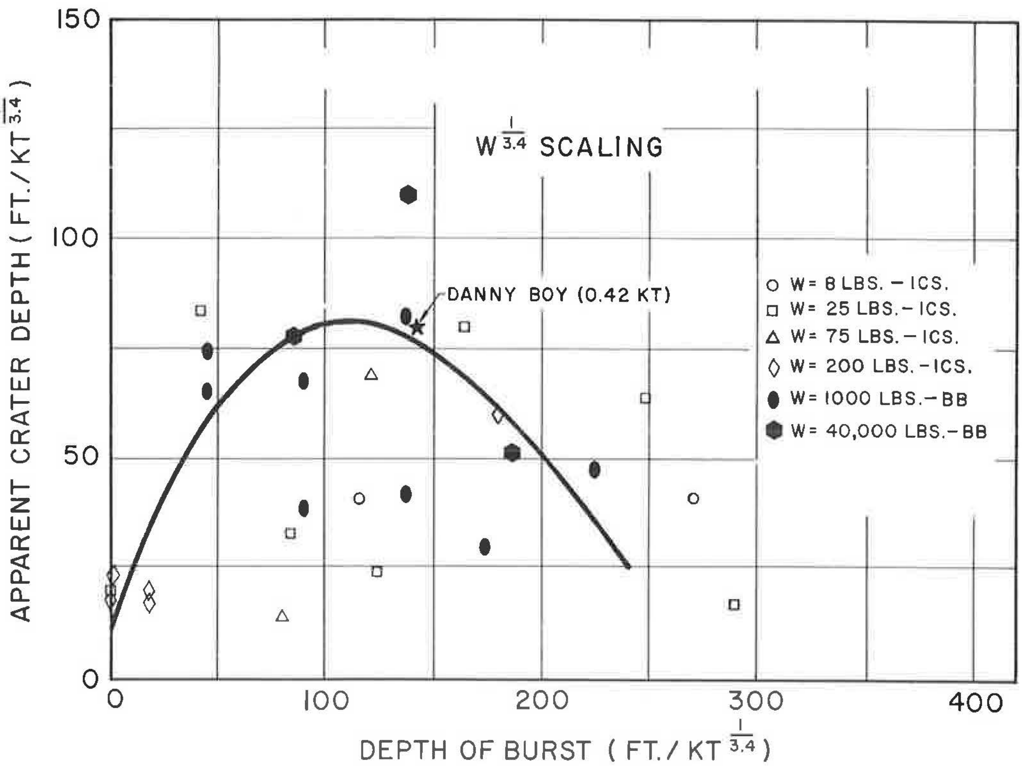

Figure 7. Apparent crater depth vs depth of burst in basalt.

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:

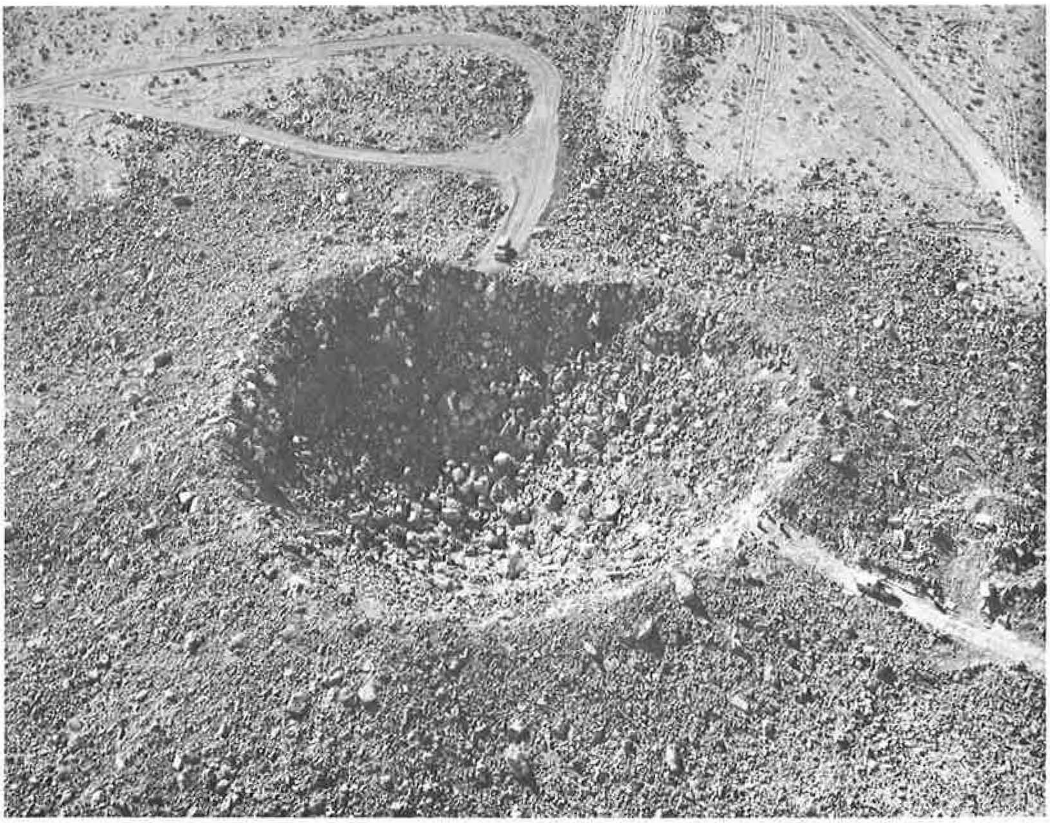

Figure 8. Danny Boy crater, 0.42-kt cratering experiment in basalt.

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 $\frac{1}{3}$ 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.

Engineering Properties and Applications Of Nuclear Excavations

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The use of nuclear excavation for engineering projects depends not only on the size of the excavation but also on the properties of the material in and around the excavation. In a nuclear excavation several general zones are evident, including the true and apparent crater, crater fallback and lip throwout material, ground upheaval, and the rupture and plastic zones. The properties of the material in these zones are dependent on original medium characteristics and the effects of the detonation.

The hyperbolic shape of a crater lends itself to good slope stability. The problem of slope stability in soils or highly weathered rock will be more acute than in competent rock. The condition of the rupture zone, the amount of surcharge on the crater lip, and ground shock from later detonations impose additional problems to slope stability evaluation. The fallback material will obtain a certain amount of dynamic compaction as a result of the material falling from heights of several hundred feet. Further foundation stability, if necessary, can be accomplished by standard techniques.

Several applications of nuclear explosives in the highway engineering field appear feasible, including excavation of roadway cuts, aggregate production by open pit mining, drainage diversion or interception by craters, and landslide removal, encouragement, or stabilization. The feasibility of using large-yield explosions for engineering projects has been demonstrated in the U.S.S.R. During the last 20 yr, many large-yield conventional explosives have been used for excavation, mining, and dam construction.

•THE PLOWSHARE program was established in 1957 to investigate possible industrial applications of nuclear explosives. Among the many applications studied, large-scale excavation is one of the most promising. Up to the present time, nuclear excavation research has been primarily concerned with developing cratering parameters to a point where an excavation can be carried out with a reasonable degree of accuracy and safety. This technology has been sufficiently developed so that specific applications can be seriously investigated as to their engineering and economic feasibility.

The use of nuclear excavation techniques for engineering projects involves not only the size of the excavation but also the properties of the material in and around the excavation. These properties affect such problems as slope and foundation stability, drainage, and other related matters. The suitability of an excavation for engineering use will largely depend on the economic considerations associated with these problems. A thorough knowledge of the site conditions and the effect of the explosion on the medium is necessary to determine the applicability of nuclear excavation to any particular engineering project.

Paper sponsored by Special Committee on Nuclear Principles and Applications.

TABLE 1

CRATERING EXPERIMENTS FROM WHICH INFORMATION ON ENGINEERING PROPERTIES HAS BEEN DERIVED

Name	Medium	Yield (kt)	Apparent Crater Parameters (ft)		
			Depth of Burst	Radius	Depth
NUCLEAR					
Jangle U	Alluvium	1.200	17	130	53
Teapot ESS	Alluvium	1.200	67	146	90
Neptune	Tuff	0.115	100	100	35
Danny Boy	Basalt	0.420	110	107	62
Sedan	Alluvium	100.000	635	600	320
HIGH EXPLOSIVE					
Scooter	Alluvium	0.500	125.0	155.0	75.0
Stagecoach No. 1	Alluvium	0.020	80.0	57.0	7.9
No. 2	Alluvium	0.020	17.1	50.5	23.6
No. 3	Alluvium	0.020	34.2	58.6	29.2
Buckboard No. 11	Basalt	0.020	25.5	44.7	24.9
No. 12	Basalt	0.020	42.7	57.0	34.7
No. 13	Basalt	0.020	58.8	36.8	16.2

A great deal of information is known about the phenomena associated with a cratering explosion (1). However, many uncertainties exist relating to the actual engineering properties of the various media which might be involved in a cratering detonation. This paper will discuss in some detail present knowledge in the following areas:

1. Engineering properties of craters produced by nuclear explosions.
2. Potential engineering applications of craters.
3. Soviet experience with the use of large-scale detonations for engineering applications.

ENGINEERING PROPERTIES OF NUCLEAR CRATERS

A nuclear crater consists of several general zones with different engineering properties. These are the true and apparent crater, crater fallback and lip throwout material, ground upheaval, and the rupture and plastic zones. The general composition and engineering properties of these zones are discussed. Knowledge of these properties is limited to investigations made on a few cratering experiments (Table 1). Figure 1, based on the Danny Boy event (2), shows a schematic cross section of a nuclear crater in a rock medium, indicating the zones of interest.

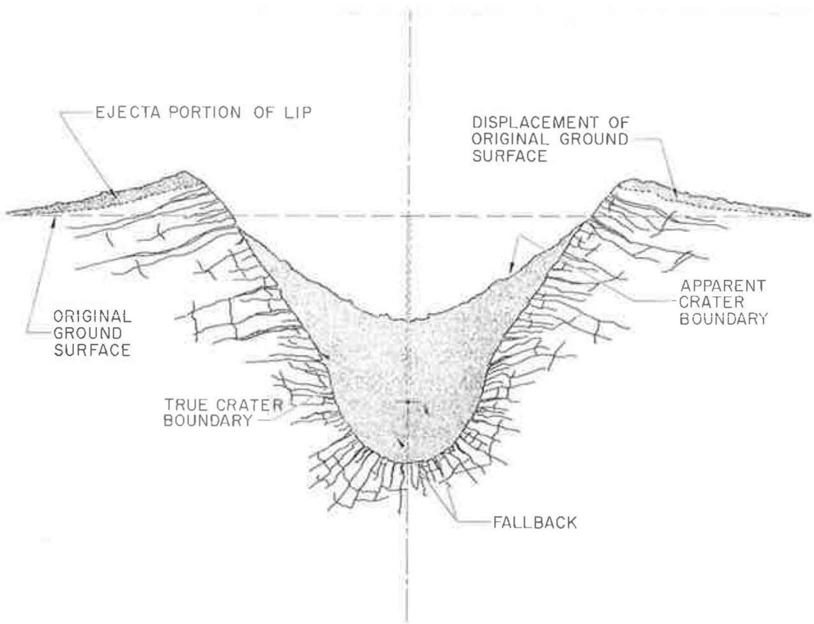

Figure 1. Schematic cross section of typical nuclear crater in rock medium, based on Danny Boy event.

Throwout and Fallback Material

Throwout and fallback material is that portion of the medium which has been put into trajectory and has fallen back into and around the crater. At the depth of burst at which maximum crater dimensions occur, about one half of the material is thrown out of the crater, whereas the remainder is fallback material. Ejecta is deposited on the lip of the crater out to a distance of about three crater radii. The fallback material is deposited in the true crater forming the apparent crater, whose shape is that of a hyperbola. Because throwout and fallback material are formed in the same way, their properties are similar. However, consideration should be given to whether the medium is relatively compressible, such as soil, or incompressible, such as rock.

Rock.—In a rock medium, the throwout and fallback material occupies a greater volume after the explosion than before the explosion. This swell is due to the increase in the voids when the natural jointing of the rock is disturbed. The rock size distribution, which affects the swell factor, is influenced by the medium, the depth of burst of the nuclear explosive, and, most importantly, the fracture pattern and soundness of the rock.

In a shallow detonation, much of the energy of the explosion is directed toward breaking up the overburden by a very strong rarefaction wave. In a deep detonation, the relatively weaker rarefaction wave breaks up less material. Thus, the ejecta and fallback material in a shallow detonation is broken at a much higher stress level, resulting in smaller particles and a low swell factor, but a deep detonation results in larger block sizes approximating the fracture pattern of the undisturbed material, producing a larger swell factor.

This phenomenon is seen in the three Buckboard cratering experiments. As the depth of burst was increased, block sizes increased. Studies are under way to better determine the rock size distribution and swell. Table 2 gives the results of a preliminary investigation based on volumetric differences from pre-shot and post-shot contour maps and estimated true crater and true lip volumes. The throwout and fallback material of the Danny Boy crater, at a scaled depth of burst of 142 $ft/W^{1/3.4}$, was determined to have a swell of about 25 percent, indicating that at the same scaled depths of burst, similar swell would be attained. With proper knowledge of the medium and careful selection of the cratering parameters, the rock size and swell factor may be somewhat controlled. The swell would also be expected to have an influence on the depth of the apparent crater. With several hundred feet of fallback material, a small change in the swell factor could affect the accurate prediction of the apparent crater depth.

Rock put into trajectory returns to the ground with great momentum. It exerts a large dynamic compaction effect on the material it hits. The compaction would eliminate weak points of contact and produce good interlocking and several points of contact between rocks (3). This tends to decrease the swell and produce a fairly stable mass. Rock flour produced by this compaction might contribute to instability; however, this would depend on the properties of the medium. Excessive rock flour has not been observed at the Danny Boy site but was observed at the Neptune crater.

Soil.—In a soil medium, the volume occupied by the ejecta and fallback material is less than the true crater volume. This difference in volume is caused by the compression and displacement effects from cavity expansion and the shock wave. An example of this shrinkage can be seen in the Sedan detonation. Based on pre-shot and post-shot contour maps, an over-all volume decrease of about 1.4 million cu yd of material was indicated. This represents about 10 percent of the true crater volume. A large amount of soil is vaporized and fused; however, compared to the total volume of material involved, this is considered insignificant. The engineering properties of the crater material, as a

TABLE 2

EFFECT OF SCALED DEPTH OF BURST ON PERCENT SWELL OF THROWOUT AND FALLBACK MATERIAL IN BUCKBOARD EXPERIMENTS

Buckboard Shot	Scaled Depth of Burst ($ft/W^{1/3.4}$)	Estimated Swell (%)
No. 11	81	10
No. 12	135	20
No. 13	186	50

whole, will not be affected by the fused material or the radioactivity resulting from the detonation.

The ejecta material, in the form of discrete masses of soil, can be observed in Figure 2. On impact, the mass distributes itself in the vicinity of the impact point. This is plainly observable in the many impact craters seen around the Sedan crater (4). The impact of this soil mass results in a great dynamic compaction on the surface material (4). Some material ejected from the Sedan detonation reached heights up to 2,000 ft. Thus, the material falling to the ground is successively compacted by subsequent falling material. A theoretical analysis of this dynamic compaction showed that soil dropped from heights of a few hundred feet would be compacted with a force greater than that of present mechanical compaction methods. Below the first few feet of material, high compaction has been observed in practice under field conditions (5).

Most throwout and fallback material in a crater formed in soil may be expected to be fairly well compacted and possess good density. Infiltration tests in the throwout material of the Sedan and Scooter craters indicated a decrease in the permeability of the material as compared to the pre-shot medium (6). Drill-hole data in the fallback material in the bottom of the Sedan crater indicate a density within 10 percent of the pre-shot density (7). Generally it may be concluded that most fallback and throwout material from a cratering detonation in soil will possess a density about the same as the pre-shot density of the material. These general conclusions must, of course, be evaluated with respect to a particular situation.

Lip, Rupture and Plastic Zones

The apparent lip of a crater is that material which surrounds the crater above the original ground surface. It is made up of the ground which has been upheaved by the explosion, the true lip, and the throwout material from the crater, the ejecta lip. The

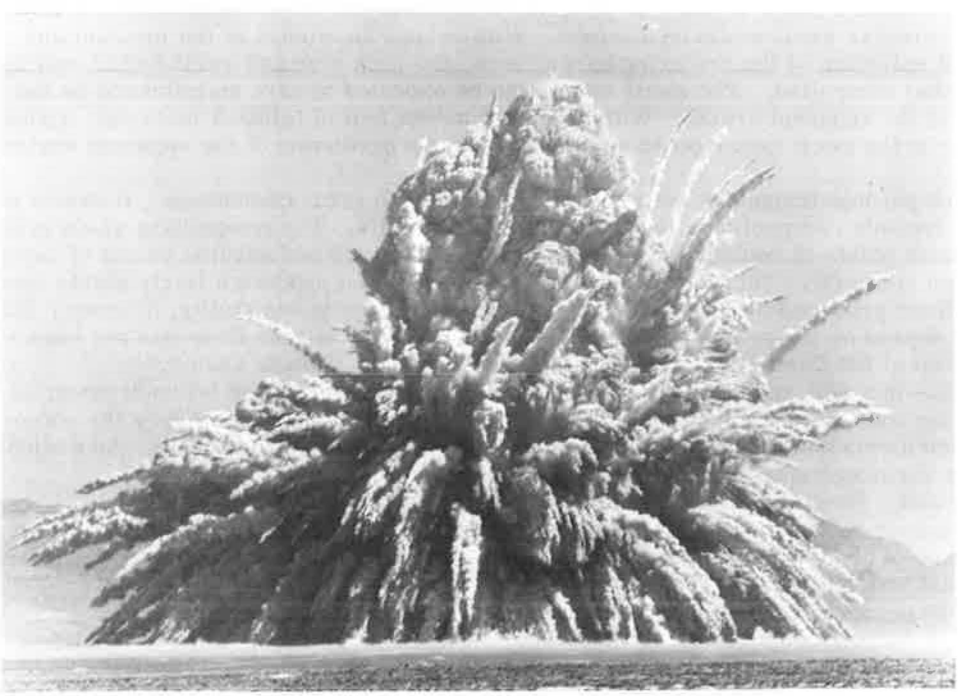

Figure 2. Sedan 100-kt detonation in alluvium, showing soil masses in trajectory up to heights of 2,000 ft.

amount of ground upheaval forming the true lip is related to the amount of distortion in the medium close to the detonation. This zone of material is called the rupture zone.

Rupture Zone and True Lip. —The surface of the rupture zone forms the true crater. In rock it is characterized by radial cracks around the cavity due to cavity expansion and horizontal cracks through the fracture pattern near the ground surface. The horizontal cracks are caused by surface spall and shear action along the true crater boundary. In soil, the rupture zone is significantly compressed around the shot point due to cavity expansion. Elsewhere, the medium is only slightly compressed by the shock wave action and the effects of cavity expansion.

These effects tend to cause an upheaval of the ground around the true crater. The Danny Boy crater had an average upheaval of 18 ft, with observed fracture pattern cracks opened as much as 12 in. (8). The Sedan crater upheaval averaged 10 ft (4). The true lip in rock is caused mainly by joint expansion, whereas in soil, displaced material from the cavity causes surface upthrust. Considering these mechanisms of formation, the true lip in a rock medium should be significantly higher than one in a soil medium.

The extent of the upheaval depends on the magnitude of the rupture zone. With an increase in the depth of burst a greater volume of the material is affected before the gases in the cavity escape to the surface, resulting in a larger rupture zone and greater upheaval. This is evident in the Buckboard experiments. As the depth of burst was increased, the height and radial extent of the lip upheaval zone increased. The upheaval around the Danny Boy crater extended out to a distance of 120 ft from the crest of the lip, a distance about equal to the radius of the crater (8).

Plastic Zone. —The rupture zone extends out to the plastic zone, where only small-scale shear failures and displacements are found. This is the transition zone between the rupture zone and the zone where the effects of the detonation on the medium have been insignificant. It is difficult to determine and has not been well investigated; however, it is felt that it exhibits no significant difference in physical properties from the original medium.

Throwout Lip. —The throwout lip is composed of the material ejected from the crater. This material falls on the upheaved true lip of the crater and out to a distance determined by the trajectories of the material. The amount of ejecta on the lip is dependent on the size of the excavation. Carlson (4) has developed a relationship between the mass of throwout material and the apparent crater volume for soil. The rock size distribution and the swell are important factors in determining throwout volume and lip height.

An interesting comparison can be made between the ejecta lips of Danny Boy and Scooter craters. The yields and depths of burst were similar; however, Danny Boy was a nuclear shot in basalt, whereas Scooter was a chemical high-explosive shot in alluvium (Table 1). The Scooter detonation was influenced by a secondary gas acceleration caused by the relatively high moisture content of the alluvium (10 to 20 percent) and the use of a chemical explosive. These factors generate a large amount of gas in the vicinity of the detonation point. This produces a sustained thrust which imparts a greater velocity and trajectory to the throwout material. Thus, the apparent crater volume of Scooter was 2.5 times that of Danny Boy. The Scooter ejecta lip had a maximum thickness of 5 ft and extended more than 400 ft from the edge of the crater. The Danny Boy maximum ejecta lip thickness was 10 ft and extended about 200 ft. Therefore, besides the differences in the medium, factors such as moisture content and type of explosive must be considered for the accurate prediction of ejecta lip parameters.

Apparent Lip. —The combination of the true and throwout lips makes up the apparent lip of the crater. Observations of many craters indicate that the lip crest occurs at about 1.2 apparent crater radii. The height of the apparent lip crest has been related to the radius of the apparent crater (4). Based on comparison of pre-shot and post-shot contour maps of the Buckboard series, the volume of the apparent lip was observed to increase with increasing depth of burst.

Apparent lip heights are not symmetrical; wide variations are evident in each crater. For example, the Sedan crater apparent lip ranged from 20 to 100 ft. This variation is probably related to unsymmetric gas venting from the cavity through weak zones in the overburden.

Lip heights in a row-cratering shot are much higher than for a single crater because in row cratering, the throwout and upheaval are confined to a much smaller perimeter. Recent high-explosive row shots in alluvium have shown lip heights to be about twice as high as the lips from a single crater (9).

Slope Stability

The most critical area of concern in the engineering use of a nuclear excavation is that of slope stability. In this respect, it should be kept in mind that standard methods of slope stability analysis are as important in nuclear excavations as in conventional excavations. Problems relating to foliation, groundwater, etc., must be thoroughly evaluated before nuclear excavation is considered. Due to the great depths of excavation economically feasible with nuclear explosives, a proper stability analysis becomes even more important (10).

Fallback Slope.—The fallback slope is similar to a talus slope, composed of broken material and concave upward with the flattest portion near the base (Fig. 1). The steepest part of the fallback slope is usually less than the angle of repose of the material. The material is thinnest where the slope is steepest. In effect, the head of the slope has little overburden and the toe of the slope is reinforced. This lends itself to good slope stability.

One obvious problem with the fallback slope is that of rockfall or erosion. Rockfall generally is of a minor nature. Large overhanging boulders and unstable sections could be scaled before the excavation is put to engineering use. The slopes are such that rocks would not tend to fall of their own accord. However, provisions should be made for adequate rockfall control, if necessary.

Erosion and mudslides might present problems in an excavation in fine-grained material. This depends on the medium, and should be thoroughly investigated. Although in an arid climate, the slopes of the Sedan and Danny Boy craters have been essentially stable since their formation in 1962.

Rupture Zone Slope.—The surface of the rupture zone generally forms the top of the apparent crater and extends downward along the true crater surface (Fig. 1). The slope of the true crater must be considered for stability of the entire excavation. The detonation would probably weaken the stability of the slope as compared to its preshot condition and, therefore, warrants special consideration.

The fractures induced in a rock rupture zone tend to slope back from the excavation. This is due to horizontal spall fractures uplifted close to the excavation. There are no major changes in the orientation of the material, and good interlocking remains. Also, the fallback material presents a large resisting force at the toe of the rupture zone. Thus, in rock, these factors should contribute to a stable slope condition. However, adverse conditions such as faults, dips, and strikes should be investigated.

A soil rupture zone slope is compressed at the base by cavity expansion and somewhat densified elsewhere due to shock wave effects. This, as well as the resisting force of the fallback material at the toe, contributes to slope stability. However, many more problems may be present to disturb the stability of soil rupture zones. For example, in some media the effect of the detonation might cause spontaneous liquefaction of the rupture zone material. The sudden removal of material during excavation could induce lateral forces from expansive properties of the rupture zone, resulting in slope failure. Slope stability conditions in soil excavations greater than a few hundred feet are relatively unknown. A great deal of knowledge must be gained before a proper evaluation of slope stability in a nuclear excavation in soil can be made.

Lip Surcharge.—A major problem relating to slope stability is the effect of the lip surcharge around the crater. This overburden adds greatly to slope instability. The lip surcharge rests on the rupture zone. Several hundred feet of lip overburden in a large excavation could, in itself, cause failure of the slope. The problem is more critical in soil than in rock. Removal of this lip material is possible but would, in all probability, be economically prohibitive. This problem becomes much more critical in row-cratering shots where the lips are higher than single shots.

Other Slope Stability Considerations. —If an excavation is to be accomplished by more than one detonation, the problem of what will happen to the slopes of a previously excavated channel exists. The shock wave from a detonation in close proximity to the excavation, in a direction longitudinal to the excavated channel, may induce large-scale slope failures.

One solution to this and other problems of definite slope instability is the intentional overexcavation of the original channel. Subsequent slides, either natural or induced, would fill up the channel to about the required depth.

Foundation Stability

If the excavation is to be used as a roadway, the question of foundation stability becomes an important factor in design. The bottom of the apparent crater consists of several hundred feet of fallback material. Earlier in this report it was pointed out that fine-grained fallback material should attain a density similar to pre-shot conditions, whereas competent rock should be well compacted, with several points of contact. Tests must be conducted to ascertain the actual bearing capacity of the foundation. In many cases, excess moisture, poor density, excessive fines, etc., require correction by standard engineering methods before a proper subgrade is obtained.

Additional settlement, if required, can be accomplished by such methods as surcharge and mechanical compaction. Fines between rocks may be washed out by water sluicing. The foundation may also be considered a subgrade with a low bearing capacity. Therefore, a properly designed flexible pavement would eliminate many problems of foundation instability. The fallback material is of a more or less homogeneous nature. Therefore, uniform settlement is expected. Differential settlement is measured and corrected, if necessary.

Summary of Engineering Properties

A rock medium is much better suited to nuclear excavation techniques than soil because of the greater stability problems encountered in a soil excavation. However, the greatest economic benefit from nuclear excavation methods is realized in rock. Each site must be individually investigated with regard to its proposed use and its properties after completion of the excavation.

Engineering properties depend on the medium, depth of burst, and yield of the explosive. Proper evaluation of these parameters yields the most economical set of conditions for the type of excavation under consideration. Thus, in the design of a nuclear excavation, the engineer must be fully aware of the effects of these parameters in order to properly evaluate the use of nuclear explosives for large-scale excavation.

APPLICATIONS OF NUCLEAR EXCAVATION

With a thorough knowledge of the technology and resulting properties of nuclear excavations, many applications become much better defined. This section is designed to introduce some of the applications related to the highway engineering field, and to stimulate thought on other possible uses. Applications concerned with roadway excavation, drainage, aggregate production, and landslide prevention and correction are discussed. It is emphasized that employment of nuclear explosives should be limited to situations where conditions allow their use. As with any general discussion of engineering methods, circumstances may exist that would prevent their use, but this should not eliminate consideration of these applications. Even if conditions rarely permit the feasibility of a project, the techniques should be well developed and readily accessible for use. The economics of these applications differ from one case to another; however, it is felt that with the proper set of conditions, nuclear techniques provide the most economic and realistic solution to many engineering problems, as well as reducing construction schedules by several seasons or years in many cases.

Roadway Excavation

The most obvious application of nuclear excavation is in the excavation of a deep cut for use as a roadway (Fig. 3). Unlike a channel excavated for a waterway, a

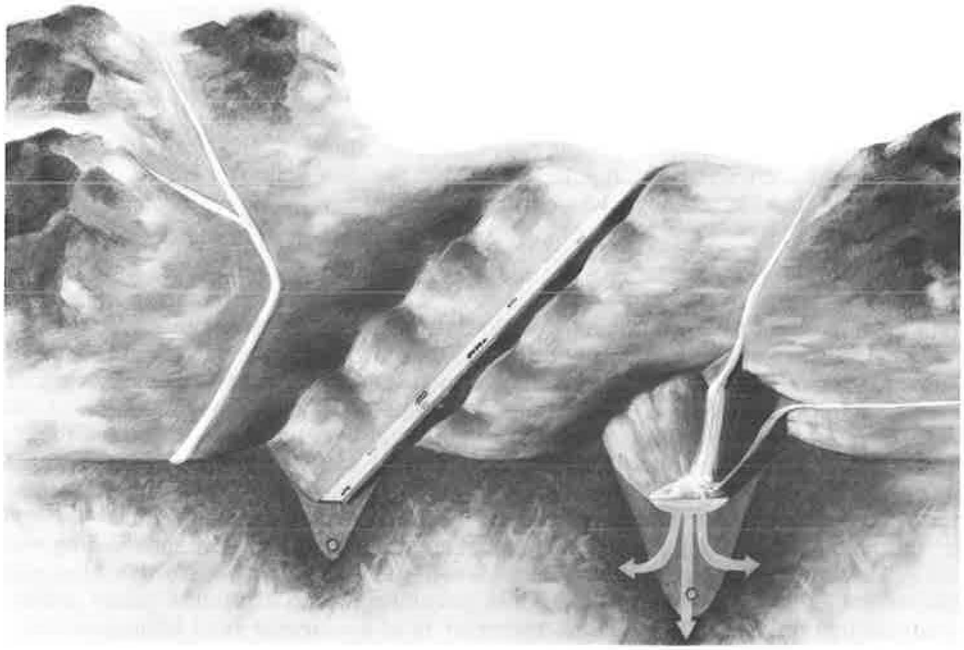

Figure 3. Potential applications of nuclear explosives in roadway excavation and drainage diversion and interception.

roadway must have a smooth bottom, close to the final design parameters. Otherwise, excessive, perhaps prohibitive, amounts of cut or fill are required to bring the roadway to the proper grade. Also the total roadway width must be such that it will fit into the bottom of the channel with adequate space for drainage and rockfall zones.

Present cratering technology indicates that the size of the excavation can be controlled by varying the yield and depth of burst. By varying depth of burst, a single yield can excavate a wide range of depths. Thus, with a relatively few standard-yield explosives, it is possible to design the excavation so that a smooth channel with approximately the desired depth is formed.

The standard use of nuclear excavation technology would lead to a re-evaluation of present highway design methods. In many cases, terrain need not be the dominating factor in determining highway routes. Studies, such as Carryall (11), illustrate that there are situations where it is more economical to design a highway through terrain requiring deep nuclear excavations than through terrain with shallower conventional excavations. Routes normally considered economically prohibitive could be undertaken. For example, Highway 40 through Nevada circumvents several mountain ranges between Lovelock and Battle Mountain, a present road distance of about 125 mi. Two 600-ft road cuts through these ranges would reduce this road distance by about 35 mi. The Southern Pacific Railway would save about 50 mi between these points. Road-user benefits by such reductions in road mileage cannot be lightly overlooked. If safety conditions such as ground shock will not allow complete excavation of a cut, it may be feasible to partially excavate the cut by nuclear explosives, conventionally excavating the fallback and rupture zone material to produce the required excavation.

One of the deepest highway excavations was at Carquinez, Calif., in 1958 (12). The maximum depth of cut was 300 ft with a volume of 8.8 million cu yd of bedded shales and sandstones, costing $0.35/cu yd for excavation and overhaul. If safety conditions permitted, a 100-kt detonation, similar to Sedan, would have excavated over 6 million cu yd of this material at less than half the conventional cost. A 50-kt detonation could have excavated almost 4 million cu yd at about two thirds of the conventional cost.

The remaining required excavation would be either in fallback or rupture zone material. Thus, conventional excavation costs would also be reduced. These comparisons are based on a total cost of $1 million for the nuclear excavation in both cases (13). In this particular case, of course, the population density in the area did not permit the use of nuclear explosives.

Drainage and Diversion and Interception

Drainage, one of the greatest concerns to the highway engineer, is a problem for which nuclear excavation techniques can provide a number of solutions. Roadway excavation with nuclear explosives will produce certain drainage benefits. In rock, the fallback material in the channel has sufficient porosity to accept all rainfall in the channel, allowing this runoff to percolate down to the bottom of the true crater and dissipate into underground permeable layers. The upheaved lip prevents runoff from entering the channel (Fig. 3) and actually diverts such runoff to lower ground for disposal. These solutions should be undertaken only when permitted by conditions considering stability and settlement.

In many situations, large drainage structures must be constructed to provide for seasonal floods or exceptional flows. The excavation of a large crater to intercept most or all flow reduces or eliminates drainage structure requirements. The water in the crater, which might otherwise be wasted, could serve useful purposes such as groundwater recharge or a water supply. The Sedan crater has a capacity of 3,000 acre-ft in surface storage and 30 percent more in subsurface storage. A crater can be produced to meet required size specifications of flood conditions up to certain limits, dictated by safety factors. A trench cut through the upheaved lip provides an access for water as in Project Carryall (11). This method is also applicable in intercepting mudslides or earth flows.

Aggregate Production

The increased requirement for road and highway construction is resulting in rapid depletion of present sources of aggregate in many locations. Low-grade aggregate and stabilization methods are being used in increasing amounts to avoid uneconomical

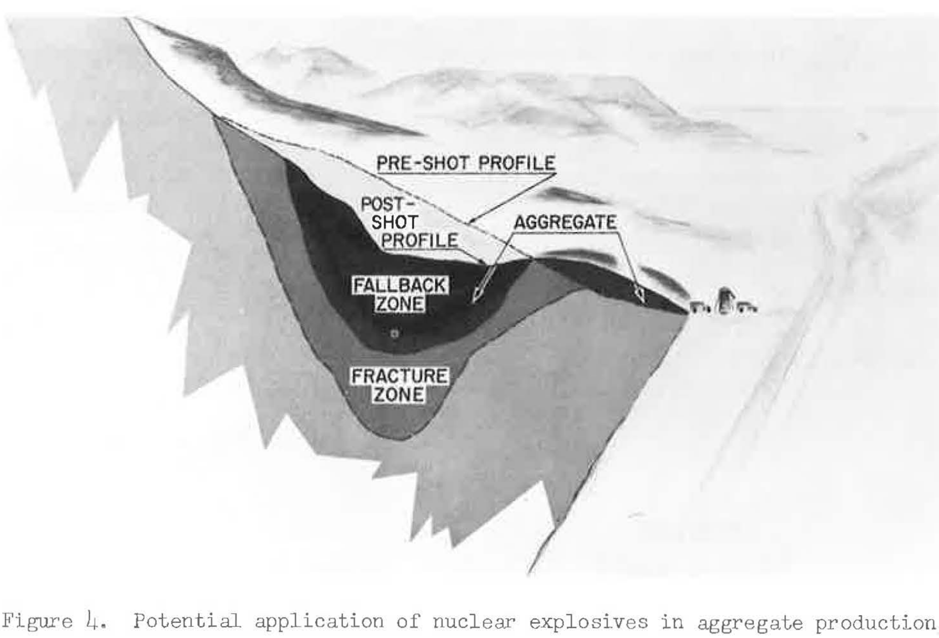

Figure 4. Potential application of nuclear explosives in aggregate production.

quarrying or long haulage. Nuclear explosives provide a method for economically breaking up a large amount of rock for use as aggregate. If the fracture pattern of the rock is sufficiently small so that secondary blasting would be minimum, a very deeply buried explosive provides the greatest amount of broken material. Otherwise a shallower detonation is required to produce smaller breakage by the action of the stronger rarefaction wave.

Access to such a quarry on level ground is difficult because of the steep sides of the crater. A quarry on the side of a hill or mountain is more feasible. The resulting crater is asymmetrical as shown in Figure 4, a scaled-up version of the Neptune crater. On a steep slope, much of the material rolls downhill with more subsequent internal grinding, producing smaller rock sizes. Neptune was detonated on a 30° slope and material amounting to about half of the volume of the apparent crater was ejected downhill (14). The "principle of directed throwout" (5) can be used to throw virtually all broken material downhill.

The uphill rupture zone slope is very steep and unstable. Most of this portion of the rupture zone would very likely collapse into the crater, providing significantly more broken material. The fractured material in the remaining portion of the rupture zone also provides a source of easily obtainable aggregate. If the detonation in Figure 4 were 100 kt, about 15 million cu yd of material would be broken up. Of this volume, about 5 million cu yd would roll downhill. The collapse of the uphill rupture zone would produce an additional 5 million cu yd and at least 15 million cu yd would also be present in the remaining portion of the rupture zone. Thus, this detonation would provide a total of 35 million cu yd of potential aggregate.

In some cases an excavation weakens a slope sufficiently to cause a major landslide to occur. This could involve a volume of material many times over the volume of the initial excavation. The Madison Canyon slide in Montana in 1959 had a volume of 43 million cu yd (15). This material was initially held in place by a buttress of outcropping quartzite and dolomite, which was buckled by an earthquake. This entire mass could have been brought down at any previous time with a properly placed small nuclear explosive. In a similar situation, large quantities of aggregate or fill material may be deposited at the base of a hill, ideally located for access and utilization.

These applications of aggregate production are also useful in the field of open-pit mining. The material which is normally ejected from the crater comes mainly from the upper portion of the medium, whereas the fallback material is from the lower levels. Thus, it is possible to remove overburden from an ore-bearing body and, at the same time, break up a large portion of the ore without excessive dilution. This same principle could be applied to aggregate production for removing overburden deposits and exposing and breaking up good quality aggregate.

Landslide Prevention and Correction

As a result of the great increases of traffic volume in recent years, requirements for shorter routes, wider pavements, and improved grades have become necessary.

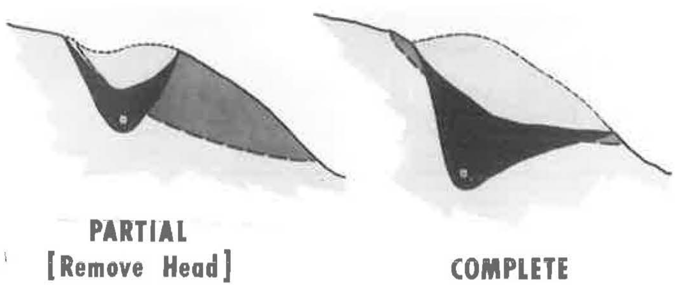

Figure 5. Use of nuclear explosives in potential landslide excavation.

The engineer is faced with deeper cuts, higher fills, and alignments which must overcome rather than avoid obstacles. Thus, the number and size of potential landslides are greatly increasing. Present solutions sometimes require exorbitant costs. For example, the filling of the reservoir behind Grand Coulee Dam by landslides has cost at least $20 million in the past 20 yr in avoidance and correction of damage. The railroad systems in the United States and Canada spend over $5 million a year on landslide prevention and correction and many State highway departments spend up to $1 million a year (16). Nuclear explosive techniques can help to reduce the cost of such solutions in the future. With the proper use of nuclear explosives, it appears possible to excavate, induce, or stabilize landslides. The relatively short time in which a device can be placed and detonated in an emergency could eliminate dangerous situations relating to landslides.

Landslide Excavation.—At the present time, potential landslide excavation is considered economical for volumes between 20,000 and 2,000,000 cu yd (16). The volume which can be excavated by nuclear explosives is determined only by safety limits in the vicinity. Thus, a potential landslide may be totally or partially excavated (Fig. 5). In a total excavation the detonation can be designed so that the apparent crater closely conforms to the slip plane of the landslide. In a partial excavation the head of the landslide is excavated, reducing the driving force of the landslide. By directed explosions (5), this material can be placed at the toe of the potential landslide for added stability. The crater also provides a method of drainage diversion under the slip plane of the landslide.

The Pacheco Pass Highway in California serves as an example of how this method may be used in highway construction. A 280-ft highway fill is being constructed in a canyon to avoid a potential landslide (Fig. 6). The volume of the fill will be 2.2 million

Figure 6. Pacheco Pass Highway in California with locations of 280-ft highway fill and slide area indicated. (Courtesy of the California Division of Highways)

Figure 7. Air view of Madison Canyon slide somewhat east of drowned toe of slide.

Figure 8. Use of nuclear explosives in potential landslide inducement by toe removal or overcoming static friction.

cu yd; the cost is estimated at about $1.5 million (17). However, the landslide danger still exists because failure will adversely affect the fill (18). A 100-kt detonation can excavate most of the slide and deposit the material into the location for the fill. The resulting crater should have sufficient volume to intercept any additional slides which might occur on the hillside opposite the fill. The canyon now has little water capacity; the crater will greatly increase this capacity and reduce the present necessity for a 9-ft concrete-arch culvert through the fill. Thus, use of a nuclear detonation will eliminate the landslide danger, reduce drainage requirements, and place the major portion of the required fill.

Nuclear explosives may also be used to excavate immediately a landslide which has blocked a valley stream or presents a generally dangerous situation. The Madison Canyon landslide blocked the valley to heights of from 200 to 400 ft (Fig. 7). Water, backing up behind the natural dam, would undoubtedly have eventually destroyed the landslide. The resultant flood would have been devastating. The Corps of Engineers spent 2 mo at a cost of $1,715,000 to develop the landslide into an earth dam. This earthwork was quite difficult and dangerous (15). A 50-kt explosive could have been placed and detonated within 10 to 20 days to completely breach the slide. If a 10-kt explosive were used, the crater produced would have disrupted the landslide enough to prevent a dangerous accumulation of water. Besides the beneficial emergency use, the economics of this application is obvious.

Landslide Inducement. —Nuclear explosives can also be used to trigger an incipient landslide in several ways, such as toe removal, overcoming static friction, or simple spalling of the complete landslide (Fig. 8). When the toe is excavated, a large resisting force is eliminated. This, essentially, was the situation at Madison Canyon. Proper knowledge of the potential slide allows an excavation sufficient to cause failure of the slide. The explosive may be placed to produce a crater within the landslide itself. The shock wave and the resulting shear forces tend to overcome the static friction forces on the slip plane and produce additional driving force on the slide area. In many cases, this is sufficient to induce slide failure.

Landslide Stabilization. —Another possible application relating to landslides is that of stabilization by a subsidence crater. A deeply buried explosive produces only a cylinder of material, collapsed into the cavity produced by the detonation, causing a subsidence on the surface (Fig. 9). This method has several advantages:

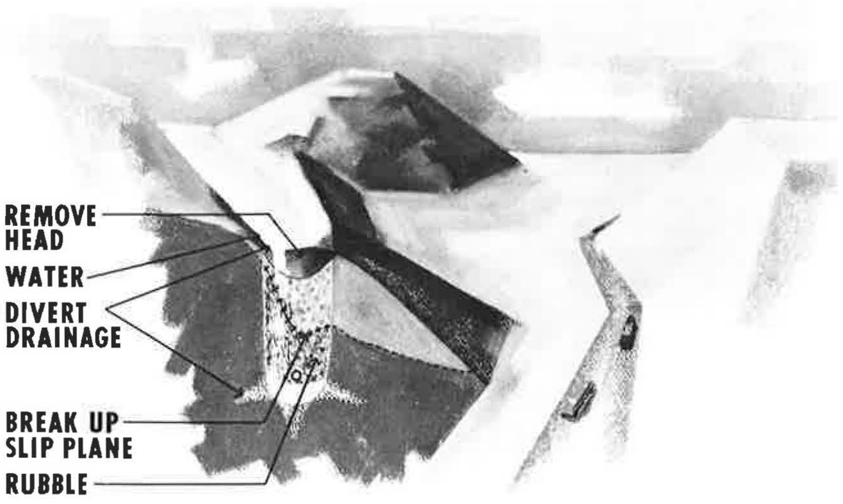

Figure 9. Potential application of nuclear explosives in landslide stabilization by use of subsidence crater.

1. The subsidence partially removes the head of the landslide, thus reducing the driving force in the potential landslide;
2. The slip plane is effectively broken up in the chimney area, which helps to stabilize the slip surface of the potential landslide;
3. Drainage is diverted from the slip plane to an area well below the potential landslide mass;
4. This method requires a very low-yield nuclear explosive, thus problems of inducing a landslide or affecting nearby structures are minimized; and
5. The detonation is almost completely contained and, therefore, the radioactivity escape is very small.

These various applications of dealing with landslides involve many problems that should be carefully considered before such a method is undertaken. However, it is felt that a careful investigation of the factors concerned will lead to many situations where one of these solutions would be feasible.

Summary of Engineering Applications

The possible applications of nuclear explosives in the highway engineering field require much further investigation before being undertaken. It is hoped that these suggestions will motivate the engineering community to their further evaluation and stimulate thought for other possible applications in the engineering field. Because of the economic and time savings possible on many projects through the use of nuclear explosives, engineers should be aware of the possibilities of this method.

SOVIET USE OF LARGE-SCALE EXPLOSIVES

Explosions in the kiloton range have been used for many years in the U.S.S.R. in the fields of mining, excavation, and dam construction:

> By explosion it is possible to excavate almost instantaneously tremendous masses of ground and obtain cuts for laying of roads or foundations ... to deepen and widen rivers and water reservoirs... to construct dams by hurling ground into river beds in such a way that this ground formed a dam of definite previously prescribed form (19).

Soviet scientists during the past few years have conducted a major program of research to develop scaling data, basic phenomenology, and operational experience in the use of chemical explosions for engineering purposes (20). Projects have been executed with great economic and engineering success. Applications on a much larger scale are planned for the immediate future.

In addition to basic research in explosion and cratering phenomena, the Soviet Union has developed the "principle of directed explosions" into an engineering tool. When a charge is detonated in the vicinity of a cavity, either on or below the surface, much of this explosive energy is directed toward the cavity (Fig. 10). The dashed line indicates surface motion from a horizontal surface. The solid line illustrates ground motion from a detonation in the vicinity of a cavity. Thus, it can be seen that the energy from a detonation is concentrated in a specific direction. If the cavity is in the form of a surface "concavity," either natural or artificially produced, this method can be used to direct throwout of material for deposition into a predetermined location. Subsurface cavities can be used to produce greater breakage, increase the volume of excavation, compact unstable soils, or remove them from below fills (21).

Using directed explosions on an incline, the main fill portion of an earth- or rock-fill dam may be placed, making use of a natural concavity (such as the bend of a river) or one produced by preliminary explosions. In seven throwout dams, about 60 percent of the throwout material fell within the prescribed limits of each dam (5).

It appears that this mass of throwout material does not conform to required construction specifications. However, according to Soviet technology,

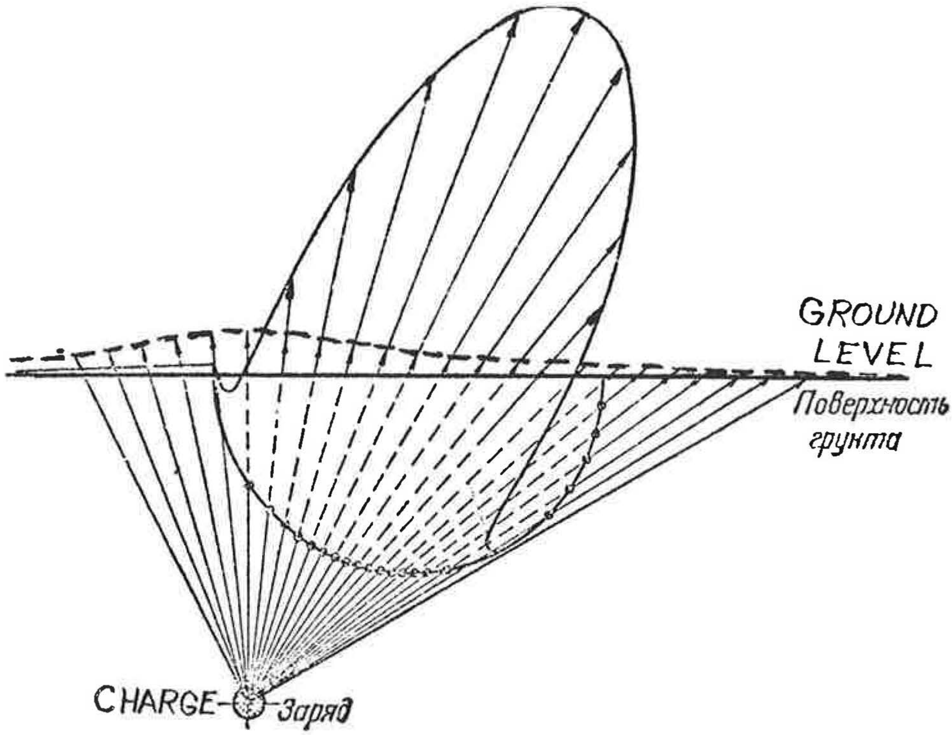

Figure 10. "Principle of directed explosions" as developed by U.S.S.R.

> Ordinarily the throwout material ... appears to be unsuitable as a solid mass for a structure which depends on the strength of the earth fill. This impression, however, is incorrect because it pertains to the surface layers of the throwout. If attention is directed to the deeper portions of the mass of material thrown out by the explosion, the impression is changed. Studies carried out in pits and bore holes indicate that the internal portions of the mass of throwout, as a rule, possess sufficient compaction and strength (5).

These applications and observations have apparently been borne out in practice. One of the best examples of the directed throwout method was in the construction of the Government Electric Station No. 1 Dam in 1943 (5). Although this was a relatively low dam (28 m), much information is known about it, and the engineering use of large explosives is well illustrated.

The original plan called for the conventional construction of two cofferdams and a diversion pipe to divert the water from the dam site. However, because construction was necessary in a low water cycle, postponement for an entire construction season would have been necessary. Therefore, it was decided to construct the cofferdams by directed explosions.

The project plan for the explosion method is shown in Fig. 11. First, a cofferdam on Channel A was constructed; this was designed to stop the flow in Channel A and reduce the flow in Channel C for 15 min. The upstream cofferdam was constructed 3 min after this, followed 3 sec later by the downstream cofferdam. Concavities were created in the right banks of the two main cofferdam explosions by auxiliary explosions, detonated 4 sec before the main charge. The parameters of the explosions and cofferdams are given in Table 3.

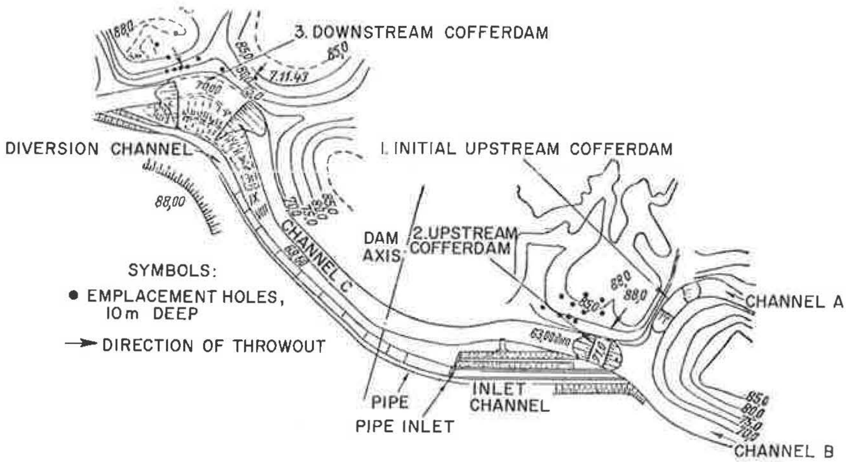

Figure 11. Project plan for construction of Government Electric Station No. 1 Dam; numbers indicating sequence of cofferdam construction by directed throwout; elevation contours in meters.

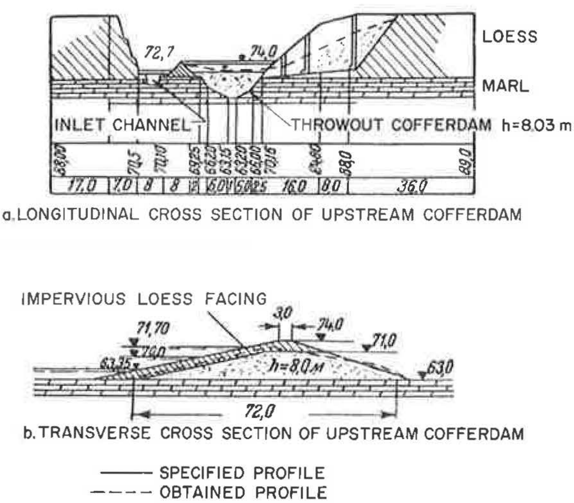

Figure 12. Longitudinal and transverse cross sections of upstream cofferdam during construction of Government Electric Station No. 1 Dam, showing pre-shot and post-shot profiles.

TABLE 3

COFFERDAM PARAMETERS FOR THE GES NO. 1 DAM

Cofferdam	Total Charge Wt (kg)	Cofferdam Ht (m)	Cofferdam Vol (cu m)
Initial	1,000	4.5	2,250
Upstream	11,500	8.0	5,000
Downstream	15,500	12.0	7,700

The resulting profiles of the cofferdams closely approximated the specifications. The longitudinal and transverse cross sections of the upstream cofferdam are shown in Figure 12. The simultaneous construction of the two cofferdams effectively diverted the water; no seepage was observed. The explosion plans were formulated in 5 days; emplacement took 4 days, and the detonation took 1 day. Thus, the cofferdams were placed and the diversion was accomplished 10 days after it was decided to construct them with explosives. This method shortened the construction period by 3 mo and saved an estimated 1 million rubles. Manpower requirements were reduced from 45,000 to 610 man-days. During construction of the main dam, 78,400 kg of explosives were detonated to direct 30,000 cu m of material into the front part of the dam spillway. In the similar construction of the cofferdams for the GES No. 3 Dam (5), settling of about 3.5 percent became stabilized within a year. No fissures or seepage were observed, and the cofferdams exceeded expectations.

This method of dam construction has been used to a certain extent in the United States. During the construction of Cabinet Gorge Dam (22), the Clark Fork River was diverted into tunnels by a cofferdam built by the displacement of 60,000 cu yd of rock from a 200-ft cliff by a 65,000-lb dynamite detonation. However, engineers in the United States generally have not practiced this method because of the general feeling that the material requires rehandling and grading to obtain a stable mass (23).

In December 1960, explosives were used in the Soviet Union to excavate a cut 500 m long for use as a railroad. A total volume of 250,000 cu m of rock was excavated. Within 4 mo after the detonation, train service on the line was opened (24). During construction of a railroad in China, a canal was excavated to cut off a meander to divert a river. Following the diversion, directed explosions were used to produce fills in the river bed for the railroad construction across the meander (19).

The largest explosions thus far reported by the Soviets have been in the mining field. Although numerous projects have been reported, the most significant one was in China in 1956. Three detonations were used to remove overburden and break up a copper ore deposit at the Bayinchansk Mine. In July, a 1.64-kt charge was detonated, followed by a 4.78-kt explosion in November. On 31 December 1956, a 9.2-kt detonation excavated 2 million cu m of overburden and crushed 7 million cu m of copper ore. This charge was buried at a depth of 60 m, producing a crater 100 m deep and 500 m in diameter (19).

The foregoing applications are but a few representative examples of the type of work with large-scale explosives accomplished in the Soviet Union. The success of this program is evidenced by the larger scale future projects that are planned. In Alma Ata a dam almost 300 ft high with a volume of 5 million cu m will be constructed by an 8.4-kt detonation. This dam is planned to stop mudslides which periodically threaten the communities in the valley (25). A 16-kt detonation is planned to excavate 5 million cu m for a road cut in the Ala-Tau Mountains (26). In Yakut two 40-kt explosions will displace 10 million cu m of earth to strip a coal layer for development (27). This project would require 8 yr by conventional mining techniques, whereas with these two detonations the time will be reduced to 2 yr. On the Angora River a 30-kt explosion is planned to excavate a 7-km channel through the Shaman-Kamen Rock (28).

All Soviet projects thus far have been conducted with chemical explosives. Published reports have indicated that future projects will also use only conventional explosives. It is not known if research is being conducted into the possible use of nuclear explosives for engineering purposes. However, the Soviets know of the great economic advantage of nuclear explosives and that radioactivity can be adequately controlled (29). The yields of the explosives for these projects are definitely in the range where nuclear explosives would be economically justified. For example, in a 40-kt detonation, conventional explosives would cost about $0.05/lb of explosive energy and would require an underground chamber with a volume of about 45,000 cu m. A 40-kt nuclear explosive would cost $0.0125/lb of explosive energy (assuming $1 million cost) and require a 30-in. hole down to the desired depth of burst. It would be reasonable to assume that serious consideration is being given to the future use of nuclear explosives.

Unfortunately, the Soviets have not published the experimental arrangements and results of their research and operations in sufficient detail to permit the incorporation of their work in our analysis. It is hoped that these data will be made available in the near future for evaluation and subsequent research. On the basis of available information, we are studying phenomena such as directed throwout and dam construction with explosives.

In summary, the use of large-scale explosives for engineering purposes has generally been proven technically and economically feasible by the U.S.S.R. Their work has been summed up by Professor Pokrovskii (19):

> In the field of study of explosion and its practical application, Soviet scientists have attained great success. There is no doubt that in the future, too, our science of explosion and of explosion technology will reach even greater progress.

CONCLUSIONS

A thorough knowledge of crater formation and the resulting properties of the medium is necessary before a realistic evaluation of an engineering application of nuclear explosives can be made. A number of areas in the highway engineering field are open to nuclear techniques, particularly in the fields of excavation, drainage, aggregate production, and landslide correction. Any possible application would require extensive study before a project could be undertaken. The success in the Soviet Union demonstrates the technical and economic feasibility of using large-scale explosions for practical engineering applications. Recent Plowshare developments have shown that nuclear explosives can be used for such projects with safety.

ACKNOWLEDGMENTS

The author wishes to express sincere appreciation to Milo D. Nordyke and Harlan H. Zodtner and other members of the Plowshare Division, Lawrence Radiation Laboratory, Livermore, California, and Mercury, Nevada, and the Nuclear Cratering Group, U. S. Army Corps of Engineers, for the information and advice that was given during the preparation of this report. Special appreciation is expressed to Carmen P. Calderon for her work in the preparation of the drafts for this report.

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Preliminary Design Studies in a Nuclear Excavation—Project Carryall

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•THE EXPANSION of population and industry in the Pacific Coast States, and particularly in California, is placing an ever increasing demand on the transportation industries operating on both rails and highways. This expansion, together with the economies found in the utilization of existing plants in the East for manufacture and the building of new plants in the West for fabrication, has made the transcontinental railway and trucking industries a network of assembly lines. Materials under load represent a huge investment unusable until delivery is made; therefore, transportation time saved may be measured in real dollars. In an attempt to keep pace with the rapid growth of both population and industry, many new Interstate Highways have been built, many are still under construction, and still more are in the planning stages. As their construction progresses, the highway transportation industry will be in a position to be a better component in the national assembly line.

In an effort to meet the ever increasing demand on the rail transportation industry, the Santa Fe embarked on a relocation study (Fig. 1) between Needles and Barstow, Calif., designed to reduce freight schedules by approximately 50 min. The most nearly acceptable route was found to the north of its present location, but the Bristol Mountains created a barrier too formidable for conventional grading equipment to remove economically. Tunneling, though technically feasible, was too expensive. At the same time, the California State Division of Highways was making a study slightly to the north of this area but still in the Bristols.

The Santa Fe, having exhausted all possibilities on the ground, turned to the Atomic Energy Commission for advice on the use of nuclear energy. A cursory investigation disclosed vast differences between conventional and nuclear method costs; conventional costs vary almost directly with the volume moved, whereas sections excavated by nuclear explosives can be enlarged considerably for very little additional cost. This gave rise to the thought of a joint venture to place the railway and highway in the same slot.

A study group was formed by members from the United States Atomic Energy Commission, the California State Division of Highways, and the Santa Fe Railway. A thorough study was made as shown in Figure 2. The Santa Fe's proposed realignment would shorten their line between Goffs and Ash Hill by 15 mi to 63 mi, and would permit higher standards of curvature and gradient. The length of highway between Ludlow and Mountain Springs would be shortened by about 10 mi. The study group determined that the railroad line could be shifted slightly to the north and the highway line could be shifted about a mile to the south, permitting the two alignments to join through the area of possible nuclear excavation. It was determined by the group that the project, insofar as the area of joint venture was concerned, was technically feasible. Costs, exclusive of the nuclear devices, were found to be much less than costs of conventional methods, and studies are presently being made to determine whether the project, Project Carryall, can now be justified economically.

An interesting note, though not applicable to this particular project, is the basic difference between the design profiles of conventional and nuclear energy constructed

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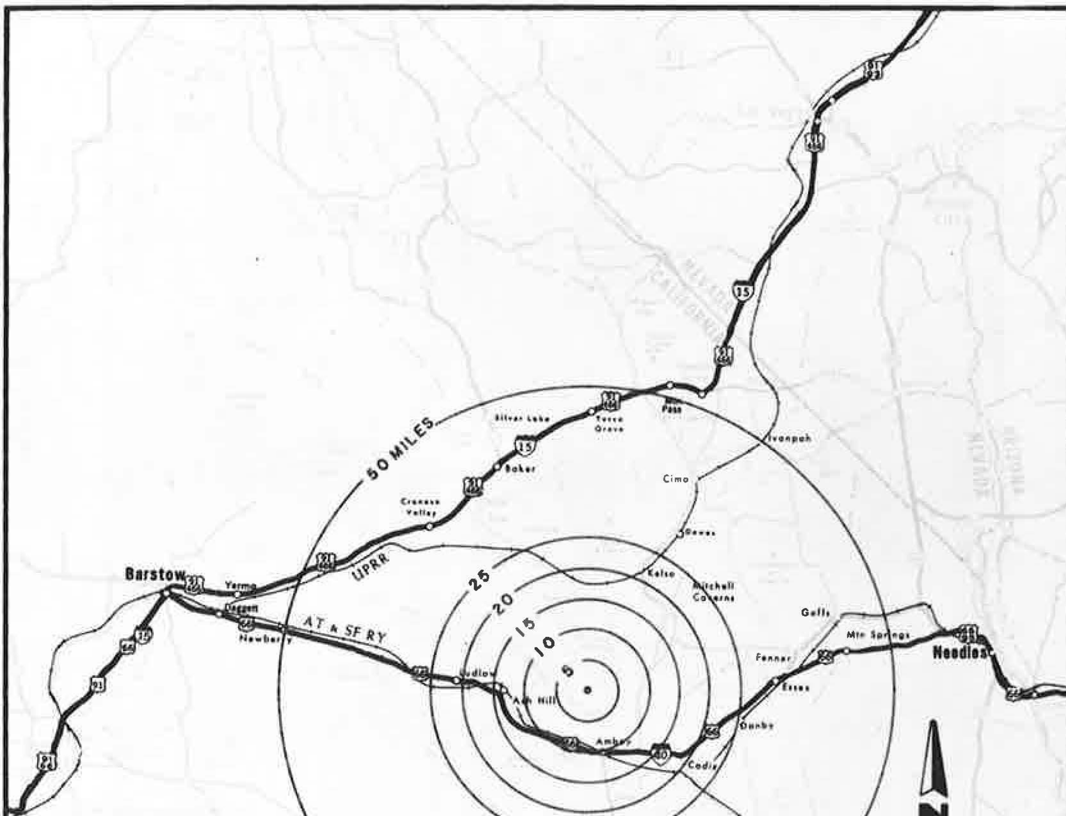

Figure 1. Area map of Project Carryall, showing radial distances from site.

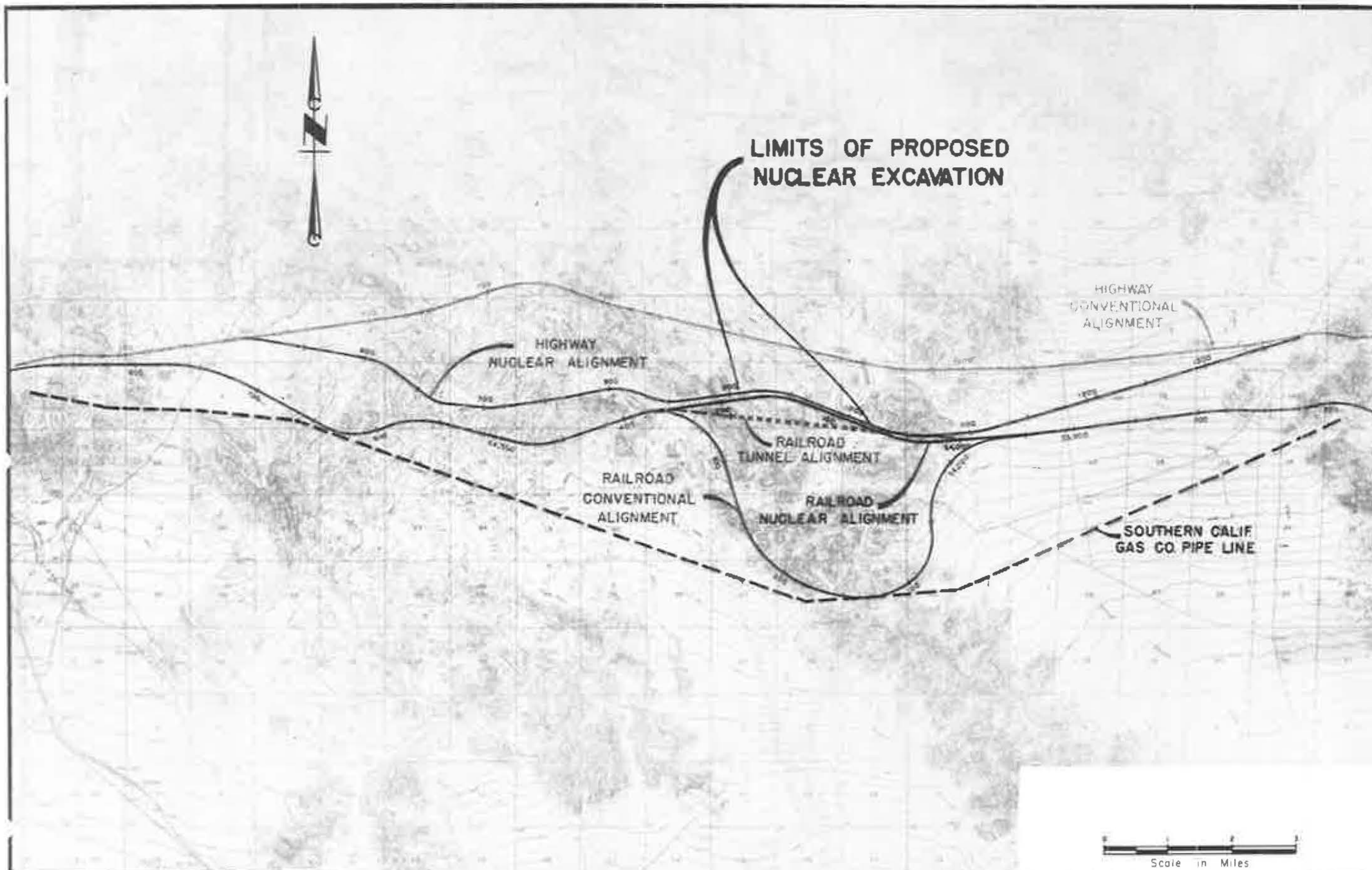

Figure 2. Study limits of Project Carryall, showing conventional and nuclear alignments.

roadbeds. Using conventional methods, balance of quantities is a principle concern and materials blasted and excavated are, more often than not, used in the construction of embankments. However, once it has been determined that an excavation is to be made with nuclear explosives, variation in depth makes little difference in cost and the cut may be deepened so as to lessen the height of adjacent embankments. This minimizes the cost of the adjacent fill and subsequently reduces the cost of drainage structures. Unlike conventional blasting, the nuclear blast not only breaks the material but also removes it, placing it on the lip of the excavation where it is available for backfill to grade in the slot or for the construction of adjacent embankments.

At this time, no subsurface exploration of the Carryall site has been made. Surface observation indicates the presence of two major rock groups. The first is comprised of Tertiary volcanics consisting essentially of hardened tuffs and harder flow rocks. The second is of hard, closely jointed and intimately fractured pre-Cambrian gneiss. No Paleozoic sedimentary rocks are known to occur in the project area. The materials to be encountered appear to have been thoroughly fractured and any handling found necessary in bringing down hazardous irregularities in slopes or in the leveling of the roadbed may be done by dozers or shovels equipped with 4-yd buckets with little or no secondary shooting.

A series of properly placed nuclear devices (Fig. 3) will produce a channel more or less parabolic in shape (Fig. 4) and reasonably free of cusps between the individual blasts. However, because some irregularities undoubtedly will occur, the bottom of the parabola is deliberately planned to be slightly below the proposed roadbed subgrade. This assures a minimum of excavation so as to avoid any possibility of removing the protective cover over radioactive debris and, at the same time, to provide additional width to receive rock falling from the slopes. Fill material required within the channel may be brought in from the ends or, where hauls would be excessive, it may be brought down over the side of the channel at intervals determined by balancing haul against the cost of moving a conveyor system or against the cleaning of the channel slope after pushing the material over the side.

One roadway of the divided freeway will be located along the bottom of the nuclear channel with the other roadway slightly higher on the northerly slope and with the railroad correspondingly higher along the southerly slope. Initial freeway construction will provide four traffic lanes (two in each direction), with room for ultimate expansion to a total of eight lanes with a standard width median.

The mathematics of magnitude of blast, spacing and depth of burial of the device, and depth and width of the resultant channel are more simple than might be expected, but a discussion is too involved for the purpose of this paper; however, the applicable equations have been graphed in Figure 5. Channel dimensions vary approximately with the $1/3.4$ power of yield and the following examples indicate the relative dimensions. The maximum device size proposed for this project will yield an energy release of 200 kt. If it were to be buried at optimum depth 675 ft below the surface of a basalt medium, it would produce a channel 370 ft deep and 1,300 ft wide at the ground surface. Dimensions diminish with depth of burial either above or below optimum burial. As shown by the dashed line in Figure 5, the same device buried 825 ft below surface would produce a channel 300 ft deep and a width of 1,100 ft. Other than to hold down radioactivity, there is no advantage in burials below optimum and drilling expenses are much higher. On the other hand, burials of less than optimum depth are objectionable because of the increase in release of radioactive materials. Until it becomes possible, however, to obtain devices having the exact yield desired, optimum burial will be rare because it will be necessary to employ the nearest but higher yield device and to bury it at whatever depth below optimum will produce the desired apparent crater depth. This problem will be resolved as use becomes more extensive.

In the event this project becomes a fact, 68 million cu yd of rock will be blasted from a channel 10,940 ft long and having a maximum depth at center line of approximately 350 ft to the roadbed. A total of 22 nuclear devices will be used, ranging from 20- to 200-kt yield with a total yield of 1,730 kt. Devices will be buried at depths

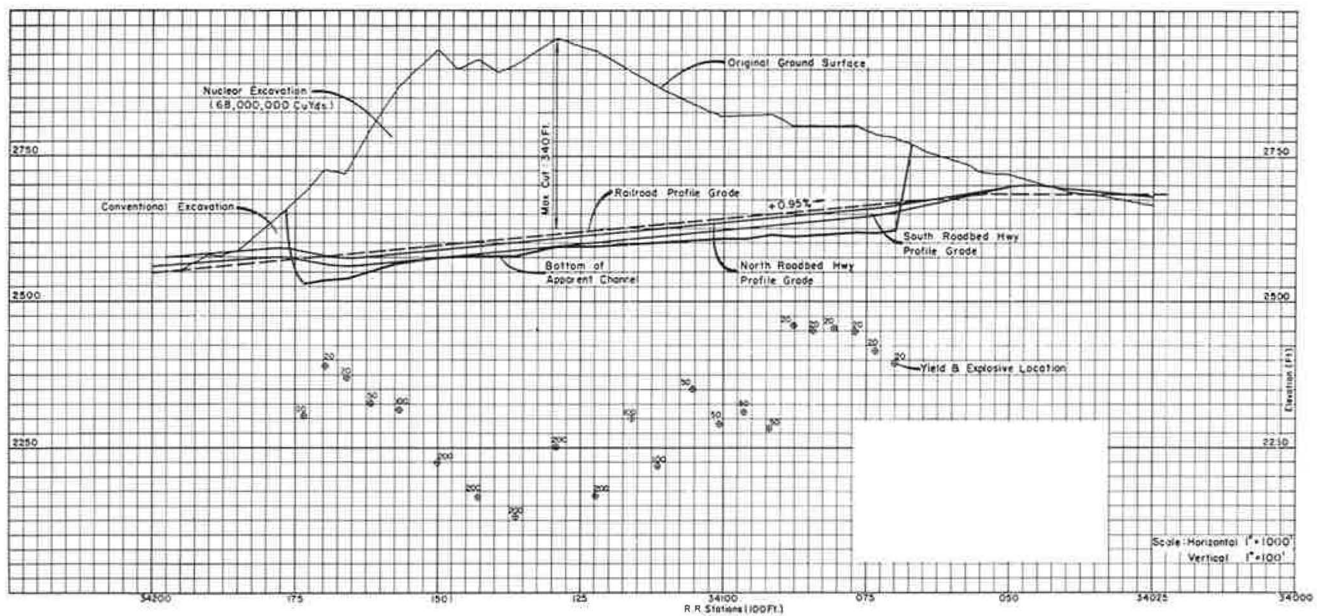

Figure 3. Excavation profile and nuclear explosive yields and locations for Project Carryall.

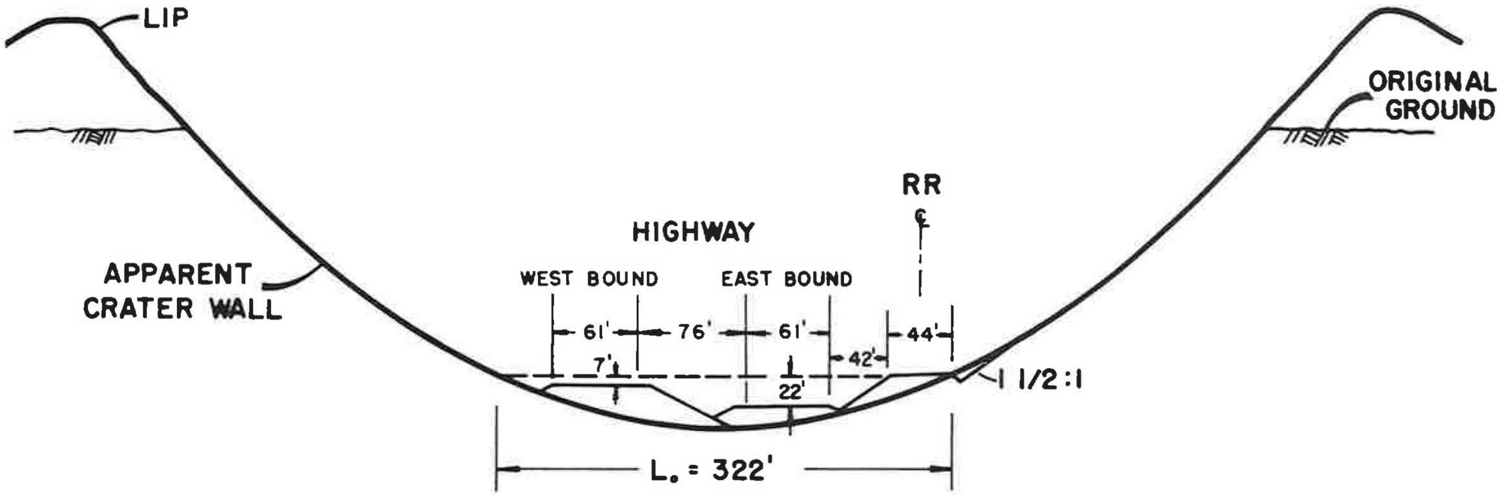

Figure 4. Typical cross section (50-kt crater) of roadway in nuclear excavation proposed for Project Carryall.

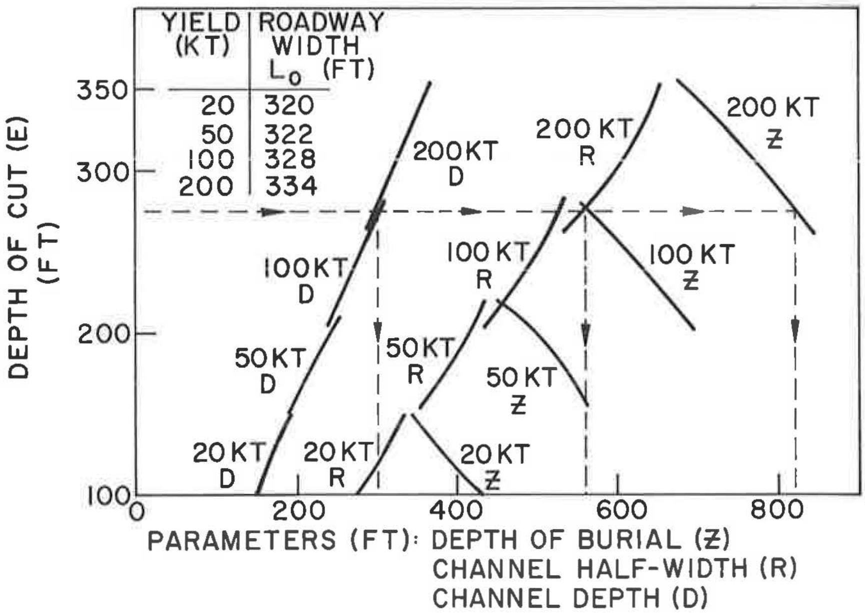

Figure 5. Cratering parameters for Project Carryall.

TABLE 1

EXPLOSIVE LOCATIONS AND CRATERING PARAMETERS OF PROJECT CARRYALL

STATION	DEPTH OF CUT E(ft)	EXPLOSIVE YIELD W(kt)	DEPTH OF BURIAL Z(ft)	CHANNEL HALF-WIDTH R(ft)	DEPTH OF CHANNEL D(ft)
34,070+00	110	20	388	290	158
073+32	120	20	372	303	168
076+83	138	20	352	325	183
080+49	142	20	348	329	185
084+16	142	20	348	329	185
087+87	150	20	343	335	192
091+90	172	50	538	383	208
096+23	184	50	517	402	220
100+61	178	50	527	394	213
105+19	202	50	485	424	236
110+32	232	100	645	481	263
115+93	262	100	588	520	292
122+25	310	200	764	608	338
129+27	340	200	705	645	361
136+23	300	200	783	596	328
143+01	316	200	753	616	342
150+01	338	200	710	641	360
156+79	280	100	555	535	309
161+78	210	50	467	430	245
166+02	140	20	350	327	183
169+72	150	20	343	335	192
173+26	114	20	382	297	162
CHANNEL TOTAL	—	1,730	11,263	—	—
ORANGE BLOSSOM CRATER	—	100	690	437	240
TOTAL	—	1,830	11,953	—	—

TOTAL LENGTH OF CHANNEL 10,940 FT
TOTAL DEPTH OF DRILL HOLES 11,953 FT

	YIELD	NO.	L_0(Ft)
	200	5	334
	100	4	328
	50	5	322
	20	9	320
TOTAL	1,830	23	

varying from 343 to 783 ft. The total depth of holes for devices within the channel will be 11,263 ft (Table 1). In addition, a single 100-kt device will open a crater to intercept and to store water from a large shed, thus eliminating rather expensive bridge structures under the highway and the railroad.

A preliminary investigation of the nuclear construction site has yet to be made. As mentioned before, only a surface study has been made at this time and a thorough knowledge of the underlying materials is imperative, because the medium encountered will have a direct bearing on the depth of burial of the devices. The area has been severely disturbed by faulting and its materials, which may have been composed at one time of large relatively unbroken masses, have been reduced to comparatively small pieces which may be ejected without further breaking. Forces required to break large rock masses are greater than those required to dislodge interlocked rock of comparatively small sizes. In fact, as the rock sizes diminish, their resistance to ejection approaches that of a granular alluvium. It is, therefore, necessary to have a knowledge of the degree of fracture before the final yield and placement pattern can be determined. It is also necessary to know whether water will be encountered, because it will contribute to the energy release and could cause serious variations from the design channel. Aside from the effect of water on the blast, it should be determined whether the water is entrapped or is part of an underground supply serving inhabited areas.

Preliminary investigation will be followed by a more precise design of the device yields required and their spacing and depth of burial will be refined with respect to the findings of the preliminary investigation.

Unpaved access roads will be constructed, where necessary, between US 66 at Amboy to the site and along the proposed location of the holes for the devices. The access roads will eventually be used for transporting the devices to the holes, for transporting personnel, and will be constructed well enough to transport a large truck crane. Dips will be provided to handle the seldom seen flows in the dry washes typical of the area and gravel plating will be placed only where necessary.

On completion of the access roads, two mobile drill rigs with wire line coring equipment will be moved in to drill 3-in. exploratory holes and to take almost continuous 1 $\frac{7}{8}$-in. cores. Holes will be drilled in the exact location of the device holes and at least to their depth of burial. As cores are taken, comparison will be made with the information used in design and if serious differences occur, depth of burial will be changed accordingly, and possibly the distance to the next hole will be slightly changed. It is important that modifications be made as the exploratory holes are drilled in order to make certain that the device holes are centered on the exploratory holes. A 5-ft relocation of the device would necessitate the drilling of another 3-in. hole. Depths will range from 343 to 783 ft and 3-in. diameter holes may cost as much as $20 per ft so a hole lost could represent a $7,000 to $15,000 waste.

For the purpose of this study it was assumed that the placement of the nuclear devices require straight holes of a 30-in. inside diameter. The actual cost of the nuclear devices is classified information, but it is certain that it is too high to run any risk of jamming one in a hole above its designed depth of burial. To avoid this possibility, and because the rock is badly fractured in its natural state, the 3-in. exploratory holes will be used to pressure grout the entire depth of the hole. The grout should extend as much as 5 ft laterally to make a solid mass of the surrounding fractured rock and thus prevent pieces from dislodging and jamming the drilling equipment. Thirty-six-in. holes will be drilled by heavy duty, tractor mounted, rotary drills drilling a 12 $\frac{1}{2}$-in. pilot hole, making a 22-in. diameter reaming, a 30-in. reaming, and finally a 36-in. reaming. Anticipated progress per hour is 5 ft for the pilot hole, 5 ft, 4 ft, and 3 ft, respectively, for the reaming. The total cost per foot has been estimated by a responsible drilling company at $115 per ft. This figure appears to be low in view of past experience, but it has been very closely supported by an estimate made by a second and equally responsible company.

There is a remote possibility that the walls of the holes will be sufficiently stabilized to permit the lowering of the nuclear devices without having them jammed by dislodged rock, but it is felt to be good insurance to incase the holes with 30-in. 12-gage corrugated metal pipe made up in 30- or 40-ft lengths welded at the joints. This is a considerably lighter gage than has been used in the past but inasmuch as this installation will not be called on to withstand forces other than its own suspended weight, it should be adequate.

It is most fortunate that the site is in an area almost entirely owned by the Federal Government and that no active improvements are in existence in the immediate area. A few mining claims are in evidence, but apparently they are not being worked. The land was used for grazing but, due to scarcity of feed, all cattle have been removed. Neither procurement of right-of-way nor property damage should pose a serious problem.

The realization of this project will mark a tremendous step forward in construction. The knowledge gained from this experience will pave the way to greater economies in the manufacture of nuclear devices, their on-site assembly, and drilling of the holes to receive them. Smaller diameter devices requiring smaller holes might well result. Certainly, even better channel dimension control will be possible. Projects, of marginal value using conventional or even today's nuclear methods, may become possible as a result of this venture.

Operations and Safety Problems Associated With a Nuclear Excavation Project

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Operational activities normally required for the conduct of nuclear explosions include such activities as pre-shot safety studies, emplacement and firing of the nuclear charges, shot time safety and control, and post-shot safety measures. For safety, engineering, and scientific reasons, the 22 nuclear explosives required for Project Carryall will be fired in two stages. When safety permits after the detonations, the site will be returned to highway and railroad engineers for roadway construction.

Safety hazards such as radioactivity, fallout, air blast, and ground shock have been thoroughly evaluated on the basis of past experience with nuclear cratering explosions and present knowledge of the Carryall area. These evaluations have shown no hazard great enough to cause significant structural damage or endanger local inhabitants. Initial site investigations will be directed toward a better definition of these problems and a more detailed description of the geology of the area.

The present Plowshare experimental program will provide additional data for the conduct and design of nuclear excavation projects such as Carryall. The time schedule for the project is compatible with the Interstate Highway completion schedule, the interests of the Santa Fe Railway Company, and the present experimental schedule of the Plowshare program.

•**THE PURPOSE** of this paper is to describe the operations and safety problems associated with a nuclear excavation project. The responsibility for operational activities required for the conduct of nuclear explosions rests with the Atomic Energy Commission and its contractors. The Atomic Energy Commission is responsible for public safety, both on site and off site, prior to, during and after a nuclear detonation.

The Carryall study is used to illustrate these problems and to suggest methods for their solution.

PRE-SHOT SAFETY STUDIES

Hydrological

Depending on the results of preliminary groundwater studies, a limited hydrological investigation may be conducted to assess the potential hazard from the possibility of groundwater contamination from fission products and/or induced radioactivity. This will probably be accomplished by continuous observations of groundwater flow rates in one or more existing water wells or exploratory bore holes in the vicinity of the experimental area. From these observations, the flow or migration rate of activities in groundwater supplies may be evaluated.

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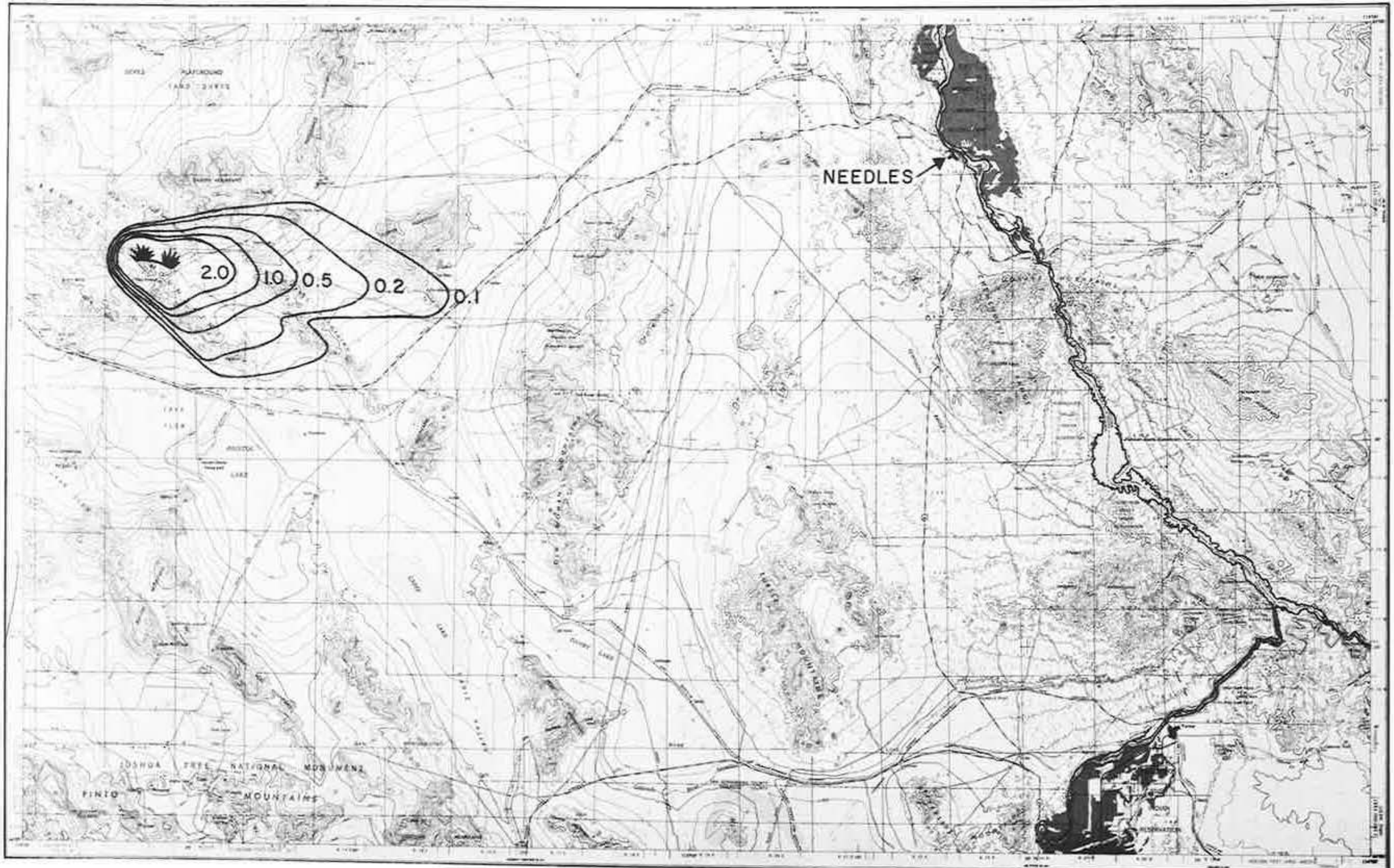

Figure 1. Fallout pattern for Project Carryall; isodose contours showing infinite dose from time of arrival in roentgens (r).

situation at shot time, a predicted fallout pattern can be calculated. In practice, to assure complete radiological safety, the shot time will be delayed until weather conditions are such that the predicted fallout pattern will not fall on an inhabited area.

Because there is a large number of "acceptable" meteorological situations, and there is no way of knowing what exact meteorological conditions will exist at shot time, two sets of winds typical for this area for the months of February and April have been used to calculate two fallout patterns, one for each detonation, using nuclear devices anticipated to be available on the Carryall time schedule. These two fallout patterns are shown superimposed on a map of the general area east of the site (Fig. 1). Shown are the infinite dose contours corresponding to the dose a person would receive if he resided at any particular place in the pattern at the time of arrival of the fallout and continuously thereafter. Experience has shown that the actual dose experienced by people averages about one half of these infinite dose numbers. Some individuals experience doses less than one half of the infinite dose, whereas a few experience doses close to the infinite dose number. If residents were evacuated for 24 hr, these infinite doses would be reduced by a factor greater than 2.

These infinite dose numbers can be compared with the Federal Radiation Council's (FRC) recommended radiation guides for individuals of 0.5 r/yr for continuous exposure. Technically, the FRC guides are in terms of rem (roentgen-equivalent-man), but for purposes of this paper this is essentially equivalent to r (roentgens). Using the 0.5 r figure, approximately 100 sq mi would require evacuation or temporary closure. The latest census data available indicate no permanent residences in the fallout area delineated inside the 0.5-r isodose line (Fig. 1).

On-Site Fallout

Based on the Sedan experience, an estimate has been made of the time when re-entry into the channel area will be permissible. This indicates that, with proper radiation protection precautions, access to the channel for limited periods of time for inspection purposes will be possible within a few days. Entry for an 8-hr workday or 40-hr workweek without unusual safeguards will be possible within a few weeks.

In all cases extensive post-shot surveys to determine the general radiation levels in the channel area, as well as to locate any "hot spots" with unusually high activity, will be made before any re-entry is permitted. Some monitoring will also be required throughout the post-shot construction phase to assure continuing safe working conditions.

AIR BLAST

Close-In Air Blast

The major problem associated with close-in air blast is related to the town of Amboy located approximately 11 mi from the detonation area in a south-southeasterly direction. Figure 2 is an aereal picture of the community of Amboy. An estimate of the air-blast hazard to Amboy has been made utilizing the data from the 0.42-kt Danny Boy event, a nuclear-cratering experiment in hard, dry basalt. An upper limit on the air-blast overpressures from a row of charges can be calculated by assuming that the air-blast waves from each explosion travel independently and are superimposed at any point of interest. Such a procedure gives a prediction for the maximum possible overpressure at Amboy of 4.3 mbars for the simultaneous detonation of the charges on the east end. The procedure is felt to be very conservative because, in reality, differing travel paths will spread the arrival times of the various waves and result in a composite pulse of longer duration but of smaller peak amplitude than direct superposition. A lower limit on the air blast can be calculated by assuming all explosions act as a single source. This will result in a peak overpressure at Amboy of 0.9 mbars. Such a range of overpressures is not expected to cause damage in a community such as Amboy, where the threshold of damage is estimated to be 10 mbars. Because Amboy is the closest community to the site and no damage is expected there, damage is not expected due to close-in air blast to any other community in the Mojave Desert area.

excavate the entire channel with one detonation. However, for the purpose of this study, excavation by two separate detonations has been used. This could be done either by excavating the central portion first, and then both ends, or one half first, and then the other half. The latter procedure has been used for evaluation of safety and nuclear operations. The final division will be made on the basis of safety requirements and the most economical engineering considerations.

Although two detonations will increase costs and time, there are several advantages in this method. Air blast and seismic shock will be significantly reduced. The maximum dose and dose rate from fallout will be cut approximately in half. Also, if two detonations are used, the channel parameters can be checked after the first detonation. This will allow any inaccuracies to be corrected in the second detonation, insuring that the channel parameters will be close to the required results. In addition, the development of nuclear excavation technology will greatly benefit by the experience of excavating a channel adjacent to an existing excavation. The ability of existing emplacement holes to hold their integrity in the vicinity of the detonation is of considerable interest. These experimental objectives can be carried out with a minimum of expenditure during this project.

Use of the three or more detonations would not significantly reduce the safety problems below their level for two detonations and would further increase time and cost. In addition, as the number of charges in a row detonation decreases below five, the row-charge effects decrease.

NUCLEAR EXPLOSIVE COSTS

The presently available schedule of charges for nuclear explosives includes such items as special materials procurement, fabrication costs, device transportation and assembly, security, emplacement, timing and firing, and safety studies. Further, these charges were predicted on the assumption of amortizing these costs over a single detonation with the statement that, "if a number of assemblies were fired in the same location, ... the ... charge per unit would be substantially reduced." In addition, in a January 1963 publication, the AEC stated:

> The single most important research advance in the Plowshare Program resulted from studies of cheaper explosives designed to produce a minimum of radioactivity....The amount charged for nuclear explosives should be considerably less in the future than the presently published estimates.

Because of these uncertainties regarding the applicability of the published charges for nuclear explosives, they have not been used in this report. Instead, the costs for device transportation and assembly, emplacement, security, timing and firing, and safety studies have been separately estimated. The cost of special material procurement and device fabrication is classified and cannot be included in this report.

SAFETY PROBLEMS

The safety problems associated with Project Carryall fall into three general categories: radioactivity release, air blast, and ground shock. Past nuclear cratering detonations have given a body of experience which can be used to evaluate generally the extent of these hazards as they relate to the specific environment to be encountered in Carryall.

Relative to off-site fallout, the cloud resulting from each of the two row detonations will be cylindrical in shape, about 12,000 ft high, and about 7 mi in diameter. The density of dust in this cloud may be such as to obscure vision during its passage within the first 100 mi. Whereas radioactivity levels in the cloud at about 100 mi do not present a hazard, it may be necessary because of reduced visibility to close highways until the cloud has passed.

Using these cloud dimensions, the total fission yield of the nuclear explosives, the fraction of the fission activity escaping to the atmosphere, and the meteorological

Air Blast

Direct and long-range air-blast studies will be conducted to predict the blast effects on existing culture in the vicinity of the experimental area and out to ranges within the possible threshold of damage. This study will include a meteorological investigation to determine under what weather conditions focusing of air-blast effects will restrict the time of the detonations.

Ground Shock

A ground shock and seismic study related to the experimental area will be made to determine the largest total detonation that can be safely fired. This study will include a detailed survey of existing structures in the area determined from the seismic studies to fall within the threshold of damage and an assessment of the damage that might be expected to these structures.

OPERATIONAL PHASE

The conduct of the operational phase of the nuclear excavation and the specifications for construction and logistics in support thereof will be under the control of the Atomic Energy Commission and the Lawrence Radiation Laboratory. Preceding this phase of the project, it is now anticipated that all initial construction and support features such as emplacement holes and roads will have been completed. It is assumed that the excavation will be accomplished by two detonations, each consisting of about 11 nuclear devices fired simultaneously.

The AEC, through its contractors, will be responsible for the emplacement of the nuclear explosives. Several device teams will be employed to achieve an emplacement time of 7 days. Before each detonation, all systems and equipment will be thoroughly checked by scheduled dry runs.

An area isolated from other activities will be provided for device storage and assembly. Earth-covered storage igloos will be constructed for device component storage. The entire assembly area will be enclosed as a security compound, with a guard station at the entrance gate.

Shot-Time Safety

Specific shot-time safety procedures will include briefings on weather information continuously collected by the U. S. Weather Bureau. This information will contain on-site and national weather forecasts. The decision to proceed with the detonations will be made by the Project Manager based on weather predictions and the recommendations of his meteorological, air blast, and radiological advisors.

Highways, railroads, and air corridors within 50 to 100 mi downwind from the excavation site will be closed for a matter of hours. All roads leading to the site will be closed. FAA will be alerted to the detonations in order to temporarily close air lanes downwind to protect aircraft from any possible air blast, dust and radioactivity.

The AEC will continue to exercise its safety responsibilities after the detonations until such time as the area is safe for re-entry and commencement of mechanical earthwork operations.

Shortly after the detonation, radiation levels in the region of the detonation will be determined by crews of ground monitors. The Project Manager will evaluate the data and determine when radioactivity has decayed sufficiently for work crews to enter the excavation. Appropriately instrumented aircraft will track the direction of the cloud and conduct aerial surveys of the fallout area. Aerial photographs of the excavation will also be taken at such time as dust conditions permit. At strategic locations around and downwind from the detonation, manned and unmanned stations will be established to record air blast, seismic intensity and fallout distribution. When the Project Manager has deemed certain areas safe for public travel, they will be immediately opened.

The number and yield of devices to be detonated simultaneously will depend on the safety requirements associated with the area. The most economical solution is to

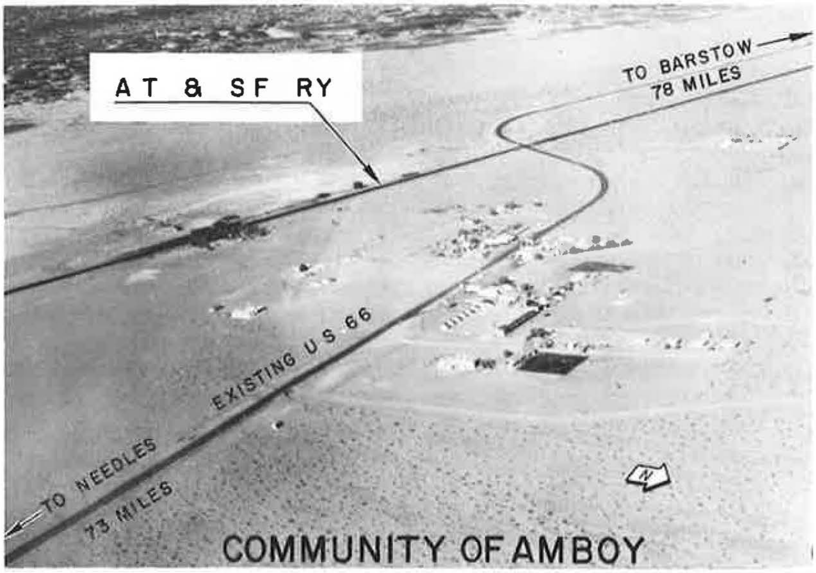

Figure 2. Amboy, showing US 66 and the Atchison, Topeka, and Santa Fe railroad line.

Present knowledge of the hydrology in the area of the proposed cut indicates that the detonation will take place in dry environment. Because of the dry nature of the medium, it is felt that the use of Danny Boy data will give the best estimate of expected blast results. However, it should be borne in mind that if the water content of the shot environment is significantly higher, as in the Sedan event, close-in and long-range air blasts will be increased. Experiments with both high explosives and nuclear explosives have indicated that the venting of a large volume of gas in the course of a cratering explosion results in the generation of an air-blast pulse considerably larger than that associated with the first motion of the ground. Thus, if an estimate of air-blast damage for Project Carryall is made based on the Sedan event results, overpressures a factor of 10 to 20 times larger than those previously used will be expected with a significant increase in the possibility of air-blast damage.

More detailed knowledge of the hydrology of the area and further study of the mechanics of air-blast generation and transmission on future nuclear cratering experiments will give data on which a final estimate of the probability of air-blast damage can be made.

Long-Range Air Blast

The Danny Boy results for long-range air blast have been used to predict that from Project Carryall. Superposition of all air-blast waves from one half of the array will result in an upper limit on the long-range air blast of 2.8 mbars. A lower limit, calculated by assuming all explosions behaved as a single source, results in an estimate of 0.65 mbars. Overpressures of 0.65 to 2.8 mbars may be expected between 100 to 150 mi. Thus, the probability of damage from long-range air blasts does not appear to be significant.

The comments relating to the importance of the water content of the medium on close-in blast apply in approximately the same proportion to long-range air blasts.

GROUND SHOCK

The maximum possible ground shock that may be experienced by the community of Amboy, calculated by assuming superposition of the seismic waves from each explosion, gives an upper limit on the predicted velocity of approximately 10 cm/sec.

Assuming all explosions acted as a single source the maximum velocity expected at Amboy will be approximately 6 cm/sec. The actual seismic shock at Amboy may be expected to lie within these two limits. The estimated threshold of damage for residences at Amboy is 8 cm/sec. Thus, it is possible that minor damage, such as cracked plaster, might occur at Amboy, but no large-scale damage is expected.

These ground-shock estimates are based on the assumption of no amplification by a deep alluvial deposit. If subsequent information discloses a much deeper alluvium, significantly higher ground shock intensities than shown here could be expected. As additional help in evaluating this aspect of the ground-shock problem, instrumentation will be included on future nuclear-cratering experiments to study amplification by deep alluvial deposits of ground shock from nuclear detonations.

A separate problem with respect to ground shock associated with this project relates to a high-pressure gas line owned by the Southern California Gas Company which passes approximately 2 ½ mi south of the proposed cut (Fig. 2, 1). This line is buried for most of its length but does include approximately 16 unsupported spans of between 30 and 70 ft. The gas line is a 30-in.-diameter ⅜-in.-sidewall steel pipe with an operating pressure of 900 psi. This pipe will, of course, experience ground shock in excess of that estimated for Amboy. Experience has shown that buried pipes are extremely invulnerable to shock and damage and none is expected in this project. The possibility of damage to the long unsupported spans of the pipeline, however, represents an area of greater concern. Preliminary analysis of the problem indicates that measures can be taken to render the probability of damage very low. Experiments with both buried and suspended pipe on future excavation experiments are planned to better evaluate the possibility of damage to this gas line.

Some pertinent information on the ability of gas lines of this nature to withstand shock loading has come from the Pacific Gas and Electric Company. They have a 34-in. high-pressure buried gas line similar to the one in question here, which crosses the White Wolf Fault between Arvin and Tehachapi, Calif. During the Tehachapi Earthquake in 1952, this fault experienced a vertical motion of approximately 2 ft in the area where the gas line crossed the fault. However, no disruption of service, damage to the line, or subsequent deterioration to the line was experienced.

DUST, ROCKS, AND EJECTA

The hazard from dust, rock, and ejecta from an excavation such as Project Carryall is limited principally to areas in the immediate vicinity of the site. The area covered by the base surge, approximately 7 mi wide extending for the length of the cut, will be covered with a coating of fine dust. Occasional rock missiles will be experienced at distances of 4,000 ft from the center line of the cut. The principal mass of the ejecta, however, will be confined to an area extending from the lip of the crater a distance approximately equal to the width of the cut. The areas involved in the mass of ejecta are shown in Figure 3. Beyond this distance, only dust coverage and isolated missiles are expected.

TIME SCHEDULE

The time schedule for Carryall must be adjusted to the construction requirements of the Santa Fe and the Division of Highways. Because the railway has no set construction schedule, the Interstate Highway schedule becomes the critical factor in determining the time schedule for the project.

A proposed time schedule for Project Carryall and Project Gally is shown in Figure 4. Project Galley is a nuclear-excavation experiment using row charges through varying terrain and will insure the proper parameters for Carryall. Other nuclear experiments are also planned. If Carryall is initiated, the study group foresees a schedule of approximately 5 ½ yr for its completion. Investigations and engineering design could begin in 1964, major pre-shot construction in 1965, and the nuclear operations in 1966. The remaining time would be required for post-shot surveys, design, grading and construction of the railroad and highway, with the pass open

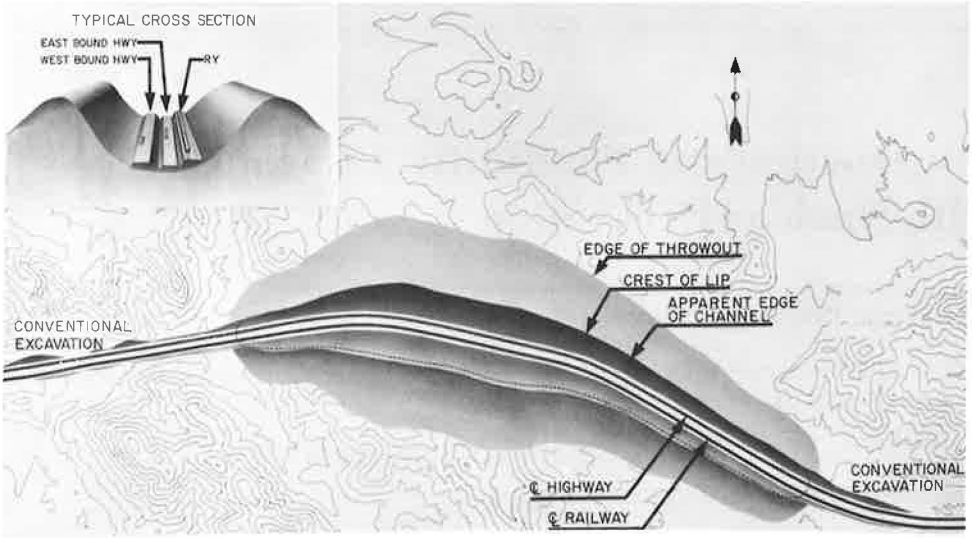

Figure 3. Plan view of the proposed Carryall excavation, showing throwout distribution.

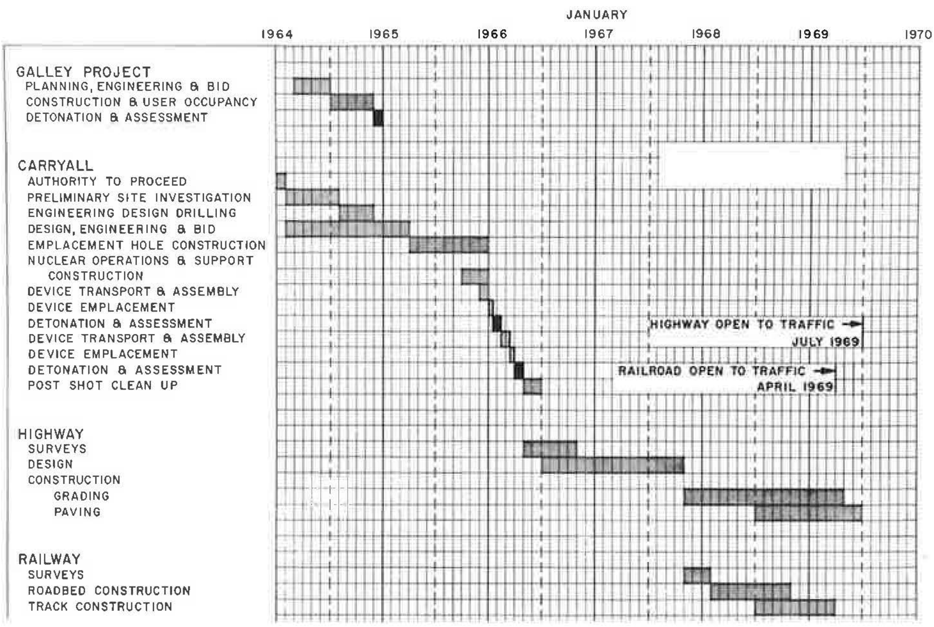

Figure 4. Proposed Carryall time schedule.

to traffic possibly in 1969. This study is only one of feasibility. There is no proposal at this time for undertaking such a project. The time schedule given, therefore, is illustrative.

REFERENCE

1. Fry, J. G., Stane, R. A., and Crutchfield, W. H., Jr., "Preliminary Design Studies in a Nuclear Excavation—Project Carryall." HRB Highway Res. Record 50, pp. 32-39 (1964).

Construction and Feasibility Associated With Nuclear Excavation

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California Division of Highways

•THIS PAPER will cover the post-shot construction, cost estimates and conclusions of Project Carryall.

POST-SHOT CONSTRUCTION

Post-Detonation Access and Engineering

Following nuclear detonations and as soon as the Project Manager has determined that radioactivity has decayed sufficiently for work crews to enter, conventional post-shot engineering activity will begin. Access roads will be constructed into the channel to permit post-shot surveys and explorations. Photogrammetric controls will then be established and the crater and adjacent areas will be mapped. Detailed and precise design of the railroad and highway facilities will then be completed—all essentially in the same manner as for a conventional project.

The cross-sectional shape of the crater will approximate a parabola and it should be relatively smooth longitudinally, with variations perhaps as great as 5 percent of the apparent crater depth. The final alignments and grades of the roadbeds will then be adjusted to most economically fit the channel.

The minimum typical cross section generally used for construction on this freeway route provides for initial construction of two 12-ft traffic lanes with an outside 10-ft shoulder in each direction and a 100-ft median dividing strip that provides width for ultimate construction of two additional traffic lanes in each direction as well as adequate width for minimizing cross-median accidents and headlight glare (Fig. 1).

Within the crater area the initial two westbound lanes will be shifted 24 ft southward from their normal position and away from the adjacent crater slope, reducing the initial median width to 76 ft. This will be done to correspondingly increase the initial width of the adjacent rockfall zone to provide greater protection during early use of the highway. Here, the ultimate additional lanes will be constructed on the outside well after the slopes have stabilized and the ultimate median width will then match the ultimate conventional construction planned to the east and west.

The design will provide for double-track railroad construction along the southern lower channel slope, with a rockfall zone approximately 38 ft wide. The railroad grade will be about 22 ft higher than the eastbound highway grade to fit the channel slope and to minimize headlight glare.

Roadbed Construction

It is assumed that all post-shot and post-survey construction work within the crater, except for railroad ballast and track, will be performed by a private firm under contract with the State in order to expedite construction without the conflict of two contractors working in the area at the same time. California's highway work is generally bid at unit prices, with comparison of bids on the basis of the Engineer's estimate. Also, the State generally specifies results rather than methods. It is contemplated that this work be so bid and performed.

Paper sponsored by Special Committee on Nuclear Principles and Applications.

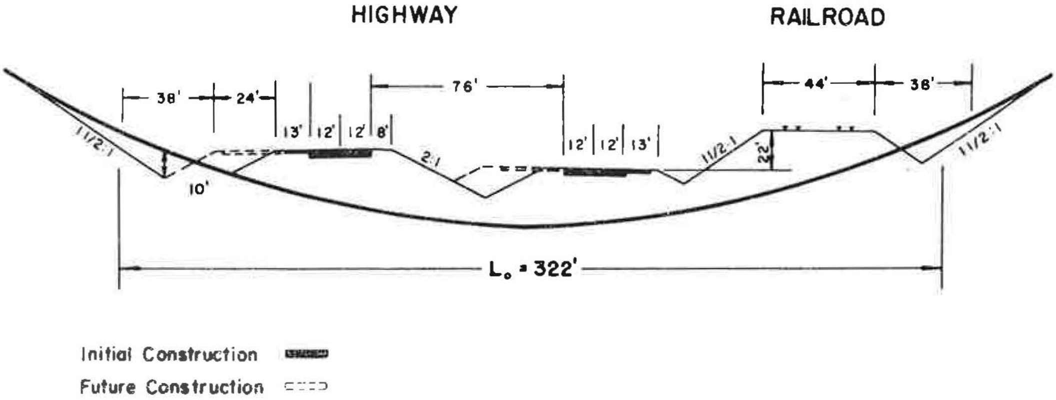

Figure 1. Typical cross section of final roadbeds proposed for Project Carryall.

The roadbeds will be constructed on embankment throughout the channel. The majority of the embankment material will be obtained from excavation areas at the ends of the channel. Because this will be predominately a rock fill, a 3-ft earth cushion is planned for the uppermost portions. This alluvium will be readily available east of the channel area. All embankment construction can be accomplished with normal construction equipment.

Rock excavation will be necessary to grade into and out of the nuclear-excavated channel. This rock has been classed as soft to medium hard, suitable for common excavation, and will be placed in the lower portions of embankment.

Excavation slopes of 2:1 ratio have been used for this study. It may be possible to increase this rate of slope to $1\frac{1}{2}$: 1 or even steeper when the actual nature of the rock is determined after detonation. All excavation construction will also be accomplished with normal construction equipment.

Previous experience indicates that the resultant material in the channel fallback area will consist of broken rock particles ranging in size up to about 2 ft. This material will be in a point-bearing condition and should be similar to a rock fill confined on the sides and bottom by the true crater.

The lower portions of the fallback material should be well consolidated as a result of the force and vibration applied by the upper layers falling several hundred feet. The use of conventional earthmoving and compaction equipment in constructing embankment on the top of this material will result in additional consolidation in the upper layers. The mantle of alluvium used in the embankments themselves will provide a cushion for the finished roadways.

With the lack of rainfall and absence of groundwater in this region, no appreciable settlement problem is expected. However, settlement platforms will be placed at the bottom of embankments within the channel, especially over the deeper shot (and fallback) locations to detect and measure possible settlement and in turn permit and check the results of corrective measures, such as surcharging or additional mechanical compactive effort. If settlement occurs subsequent to construction and during use of the railway and highway facilities, it should be of a relatively uniform character and can be corrected by adjustment of the railroad track and ballast and, on the highway, by resurfacing with asphaltic concrete pavement.

Because this excavation will be in areas of medium hard to hard rock, the slope stability problem is more nearly related to the properties of the rock in the rupture zone outside the true crater walls than to the fallback in the crater. The stability of the material in the rupture zone depends on its resistance to shearing stresses imposed by the added load of the lip material. Because the thickness of overburden in this area is negligible, it can be assumed that the rock in the lip will be resting directly on rock in the rupture zone.

The character of the material involved will be determined during the preliminary site investigation phase. Additional channel width to provide a greater width of rockfall zone can then be planned to allow additional room for possible slides if conditions warrant. The added cost of increasing the device yield to allow for this extra width is relatively minor.

It is expected that the fallback material will reach a natural angle of repose shortly after detonation, except for minor raveling.

Post-shot investigation will be made of the possible need for scaling of loose rock and removal of potential slide material from the slopes. If indicated, this will be required of the construction contractor as a first order of work.

Drainage

Preliminary investigations indicate that the voids in the channel fallback zone will be more than capable of absorbing all runoff from rainfall within the channel area. The depressed rockfall zones along each side of the channel will be extended with sidecut ditches at the western end which will provide outlets in the event the fallback zone becomes incapable of absorbing the entire runoff. Preliminary indications are that groundwater does not exist within the channel area.

Runoff from a minor drainage area south of the channel, and near the eastern end, will be diverted by the channel lip into the Orange Blossom Wash without crossing either the railroad or highway roadbeds. Another drainage area south of the channel and near the western end will probably be handled by dropping the flow into the adjacent rockfall zone and drainage ditch sloping to the west.

Orange Blossom Wash crosses the eastern end of the proposed nuclear alignment. Here the proposed roadbed grades are at elevations below the present flow line of the wash. One solution is to divert this flow east to a point where roadbed elevations permit passing it under bridges. However, the cost of three major bridges plus channel, dike and riprap slope protection construction would be quite high.

In lieu of such conventional construction it is proposed to handle the runoff from this wash and a smaller drainage area to the west by providing a separate nuclear crater in the bed of the wash upstream from the highway and railroad crossing (Fig. 2). A relatively minor amount of cutting through the lip will be required to train the

Figure 2. Model of Project Carryall showing drainage crater in relation to roadway excavation.

runoff into this crater, and a culvert will be provided to pass the runoff generated between the crater and the highway and railroad.

The maximum known thunderstorm occurring in this area was of 7-hr duration with a peak intensity lasting 3 hr. It is estimated that such a storm will deliver 3,450 cfs to the proposed crater for 3 hr with a total runoff volume of 850 acre-ft. This crater will be excavated with a 100-kt device and will be designed to provide an apparent crater volume of about 1,600 acre-ft. The voids in the fallback material between the limits of this and the true crater will add considerably to the safety factor. The water trapped in such a crater will be dissipated by evaporation and possibly some seepage (1, Fig. 3).

With the storage capacity provided and the infrequency of thunderstorms at any one location, particularly of the magnitude of the design storm, this design should provide adequate protection.

COST ESTIMATES

Conventional Solution

The Santa Fe's most economical conventional construction (although not economically feasible) is the "Tunnel Route." The cost for the 4.34 mi of railroad, including 12,800 ft of double-track tunnel, is estimated at about $14.5 million. Almost $10 million is for tunnel construction.

To provide a basis for comparison of highway costs, a distance of 18.03 mi from divergence to convergence of the highway conventional and nuclear routes was used. The estimate for construction on the conventional route is about $7.2 million.

Nuclear Solution

The nuclear solution will first involve a cost of about $330,000 for additional preliminary engineering studies and site investigations. About two thirds of this is for exploratory drilling. The next phase will include construction of access roads and exploration and cased emplacement holes at each device location. This work will cost approximately $2.3 million, about one half for the 30-in. emplacement holes.

The nuclear operations costs are estimated at about $1.9 million. These costs include additional pre-shot safety studies, emplacement and firing, shot-time safety and control, construction of facilities necessary for emplacement and detonation and post-shot safety measures. They do not include charges by the Government for the nuclear explosives.

The post-shot construction costs for the railroad are estimated at about $2.9 million. A great portion of these costs is for grading into and out of the channel. The post-shot highway construction costs for the 18.11 mi used for purposes for comparison are about $6.3 million.

Comparison of Solutions

In comparison, the total cost to the two agencies each on its own conventional alignment and using conventional construction methods will be about $21.8 million, whereas the total estimated cost of the Project Carryall nuclear solution is $13.8 million, an apparent reduction in cost of about $8 million. These figures do not include the charges by the Government for the nuclear explosives.

Cost of Nuclear Solution if Done Conventionally

Although perhaps not pertinent, it is interesting to note that the cost of excavating a cut at this location by conventional methods and comparable to the proposed nuclear cut would probably cost at least $50 million for the 68 million cu yd of excavation involved.

GENERAL CONCLUSIONS OF THE JOINT STUDY GROUP

Technical Feasibility

Based on the results of this study, this project is deemed by the study group to be technically feasible.

1. It is considered possible, based on present data and technology, to excavate with nuclear explosives a cut of the required length (approximately 2 mi), bottom width (approximately 325 ft), and depth (between 100 and 350 ft), involving the removal of 68 million cu yd of material.
2. There are no obvious safety problems that would prohibit its conduct.
3. It is considered reasonable to predict that the cut can be made so that the grade required for the highway and railroad will be established within the limits of ± 5 percent.
4. The engineering characteristics of the resultant cut, such as slope stability, rock size, and compaction, will make it possible to construct a railroad and highway through the cut, using conventional construction techniques without inordinate or extraordinary costs or other measures.
5. Although the excavation technology is not completely established and the devices considered optimum for the project are not presently available, their availability is considered to be a reasonable extrapolation of existing technology and currently available devices.

To minimize the post-shot earthwork and to have the safety problems well defined, three projects currently planned as part of the Plowshare nuclear-excavation program (Buggy, Schooner, and Galley) should be conducted in advance.

The projected time schedule for development of appropriately designed nuclear explosives, the conduct of the prerequisite experiments and the completion of the project are compatible, from a technical viewpoint, with the Interstate Highway completion schedules and the desires of the Santa Fe.

Scientific Benefits

The execution of Project Carryall will provide much data of vital significance to the development of nuclear excavation technology. Its value as a demonstration of the safety, practicality, and usefulness of nuclear excavation and the interest generated in similar projects will, of course, be of major significance. But there will be many other scientific and engineering benefits of a much more real and lasting nature. These include:

1. Confirmation of the accuracy of prediction techniques for row craters in a new medium through irregular terrain at yields significantly larger than any previous row experience;
2. Data on the immediate and long-range slope and foundation stability of crater slopes;
3. Data on the suitability of crater fallback debris for heavy construction purposes and the accommodation of surface drainage;
4. If fired in two or more detonations, the information on interaction between an existing crater and an intersecting crater; and
5. Additional data on the nature of safety questions associated with rows of nuclear charges.

Such information is essential to the orderly development of nuclear excavation as an engineering tool and its ultimate use as a construction technique, and it will be of significant worth to the Plowshare program.

Economic Feasibility

As previously mentioned, the cost of the nuclear solution is estimated to be about $8 million less than the conventional solution, exclusive of charges for the nuclear explosives.

This figure, however, is meaningful only for the purpose of demonstrating the economic advantage of the nuclear solution over the cheapest combined conventional solutions. The State's alternate, and conventional, solution is feasible, whereas the Santa Fe's is not. The amount the latter could expend within this area on an economically feasible realignment would be considerably less than the $14.5 million estimated for their 2-mi tunnel plan.

The practical economic feasibility is contingent on the amounts the Santa Fe and the State could economically contribute toward the nuclear explosive costs, the charges the Government would make for the explosives, and the degree of participation by Plowshare in such a project. This may be determined and resolved by pending decisions by the management of the three agencies.

REFERENCE

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