EXCAVATION I

SUMMARY OF NUCLEAR-EXCAVATION APPLICATIONS*

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ABSTRACT

Although many nuclear-excavation applications have been proposed, few have been seriously considered and none have been brought to fruition. This paper summarizes and discusses specific examples of a canal, a harbor, a highway cut and a nuclear quarry, all of which have been studied in some detail. It is believed that useful demonstration projects—such as a deep-water harbor and a nuclear quarry—can be safely accomplished with existing technology. Current assessments of the feasibility of constructing a sea-level canal in either Panama or Colombia appear to be favorable from a technical viewpoint. The concept of close spacing in row-charge designs has made it possible to greatly reduce the estimated required salvo yields for both proposed canals. Salvo yields have been reduced from 35 Mt to 13 Mt in Colombia and 11 Mt in Panama. As a result, the seismic motions predicted for large cities in these countries are similar to motions produced in populated areas in the United States by nuclear tests and earthquakes in which no real damage to residential or high-rise structures was noted.

INTRODUCTION

Ever since the Plowshare program was formally established in 1957, many potential applications for nuclear excavation have been proposed and reported.[1,2] Although none of these proposed applications have been brought to fruition, a number of them appear to be economical as well as feasible from a technical and public-safety standpoint. Continued progress has been made in improving excavation techniques, in developing improved explosives, and in predicting effects, including seismic motions, radioactivity, and air blasts. This paper reviews and summarizes major excavation applications that have previously been reported in detail and analyzes them with respect to current technical knowledge. The general applications discussed are canals, harbors, highway cuts, and nuclear quarries.

TRANSISTHMIAN SEA-LEVEL CANAL

The most detailed and costly investigations and studies so far conducted by the AEC, its contractors, and the Corps of Engineers have been for the most ambitious project yet contemplated—a transisthmian sea-level canal. A recent evaluation of this project by the Lawrence Radiation Laboratory, Livermore, has led to a significant reduction in the individual and salvo yields deemed necessary in earlier studies.[3] These reduced yield requirements resulted from information gained in recent cratering experiments, from the adoption of a family of explosive yields with smaller

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incremental steps, and from taking advantage of the enhancement of single-charge dimensions that is inherent in multiple row charges. As a result, the largest single salvo yield of 35 Mt has been reduced to 13 Mt for Route 25 in Colombia and 11 Mt for Route 17 in Panama. The significance of this reduction is that the seismic motions predicted for large cities in these countries are now similar to motions produced in populated areas in the United States by tests at the Nevada Test Site and by earthquakes for which no real damage to residential or high-rise structures has been noted. Of equal importance from a feasibility standpoint is the fact that the largest single-charge yield is now 3 Mt. If the experimental program progresses as scheduled, then within a year this yield will be less than a factor of 5 higher than existing cratering experience, and the uncertainties in the scaling dimensions over this range amount to only 10%.

A. The Close-Spacing Concept

The single most important factor in reducing individual and salvo yields is the enhancement of row-crater dimensions over that of single-crater dimensions. The amount of enhancement or increase above the maximum single-crater dimensions at a specified yield is related to the spacing between the explosives and to the depth of burst. Enhancements of 25 to 40% are readily achievable in row-crater dimensions, yet single-charge yields would have to be increased by a factor of 2 to 3 to produce similar single-crater dimensions. In essence, the apparent yield of the explosives in a row charge increases as the charges are brought closer together due to interaction between the charges.

The amount of enhancement achievable appears to be controlled mostly by economics. The cost of nuclear excavation is virtually a linear function of the number of explosives used rather than the yields of the explosives. For example, the projected charge is about $500,000 for a 200-kt explosive and only $600,000 for a 2000-kt explosive. The need for one additional explosive and its accompanying emplacement hole at $200,000 to $500,000 quickly eliminates the justification for a close-spacing concept except in large projects like a sea-level canal, where the nuclear-excavation cost is minor in comparison to the total project cost, or in projects where a substantial reduction in seismic motion is the overriding factor.

When the spacing between the explosives in a row charge with a fixed number of explosives is gradually reduced, the row crater becomes shorter and shorter and more and more elliptical until a single-charge-like crater is formed whose dimensions are proportional to the sum of the yields of the individual explosives. In the existing canal studies, a minimum ratio of 2 between the crater length and the crater width has been selected. This is achieved with five explosives, assuming enhancements of 25 to 30%.

Although a sufficient number of chemical-explosive row charges have been fired to support the concept of enhancement through close spacing, an insufficient number of chemical-explosive rows and no nuclear-explosive rows have been detonated to definitely establish the spacings and depths of burst required for specific enhancements.

Estimates of the required spacings and depths of burst are given by two different analytic procedures. The first procedure, which is described in Appendix A, assumes that the velocity fields of adjacent charges add vectorally and that the resulting velocity field or mound velocity is comparable to that of a single higher yield explosive at the same actual depth of burst. This general approach was used successfully in designing the nuclear row experiment, Buggy I.[4] The second procedure assumes that regardless of the spacing, there is a constant enhancement of the volume of material excavated by each row charge over that excavated by an optimum single charge. For a specified enhancement of the linear dimensions of a row, this procedure selects a spacing that provides the predetermined apparent crater volume for each row charge.[5]

As a first approximation in the second procedure, the depth of burst for a row of explosives is based on the apparent yields of the explosives. A 30% enhancement of row-crater dimensions would therefore require the explosives in the row to be buried 30% deeper than is optimum for the actual explosive yields. If the burial depths are not increased in this way, the increase in explosive energy per unit length (i.e., the apparent increase in the individual explosive yields) results in the apparent depth of burst for the row being shallower than optimum. Consequently, the enhancement of the row-crater dimensions is reduced and the crater depths tend to expose the shot points, as was evidenced in the Pre-Gondola III row-charge experiment.[6] In this experiment, the crater half-width was enhanced by 23% over the apparent radius of a single crater (R_a) and the crater depth was enhanced by 38% when the depth of burst was increased to about 10% deeper than optimum. The crater depth virtually exposed the shot points. In a follow-on experiment performed by the Nuclear Cratering Group at LRL, the crater half-width was enhanced by 36% and the apparent depth by 38% when the depth of burst was 29% deeper than optimum.[7] These latter enhancements were produced at a larger spacing (0.7 $R_{a_{max}}$) than that used in Pre-Gondola III (0.6 $R_{a_{max}}$).

Figure 1 illustrates the concept of close spacing with a typical cratering curve. Points A, B, and C represent the scaled dimensions of three rows of charges at the same depth of burst but with three different spacings. In row A, the spacing between the explosives is too large and there is no increase in dimensions over those of the optimum single-charge crater. The apparent yields of the row explosives are still larger than the actual yields, for the dimensions are larger than those of a single explosive at the same depth of burst. The apparent yield of the explosives in row A is given by

$$W_{ap} = \left(\frac{OA}{OA'}\right)^{3.4} W ,$$

where W_{ap} is the apparent yield, W is the actual yield, and OA and OA' are distances taken from Fig. 1.

In row B, the spacing and depth of burst are optimum. The increase in dimensions over those of the optimum single-charge crater is proportional to the apparent yield of the row explosives, or (OB/OB') = (DB/DA). The apparent yield of the explosives in row B is given by

$$W_{ap} = \left(\frac{OB}{OB'}\right)^{3.4} W .$$

In row C, the spacing between the explosives is too close for this depth of burst. The dimensions are much larger than those of the optimum single-charge crater, but the enhanced dimensions are not proportional to the apparent yield of the explosives. The apparent yield of the explosives in row C is given by

$$W_{ap} = \left(\frac{OC}{OC'}\right)^{3.4} W.$$

The expected dimensions at the optimum depth of burst for the spacing in row C are shown as point C''. The apparent yield of the row explosives is unchanged since point C'' is plotted in such a way that (OC/OC') = (OC''/OB').

The increase in the dimensions of row C'' over those of the optimum single-charge crater is now proportional to the apparent yield of the row explosives.

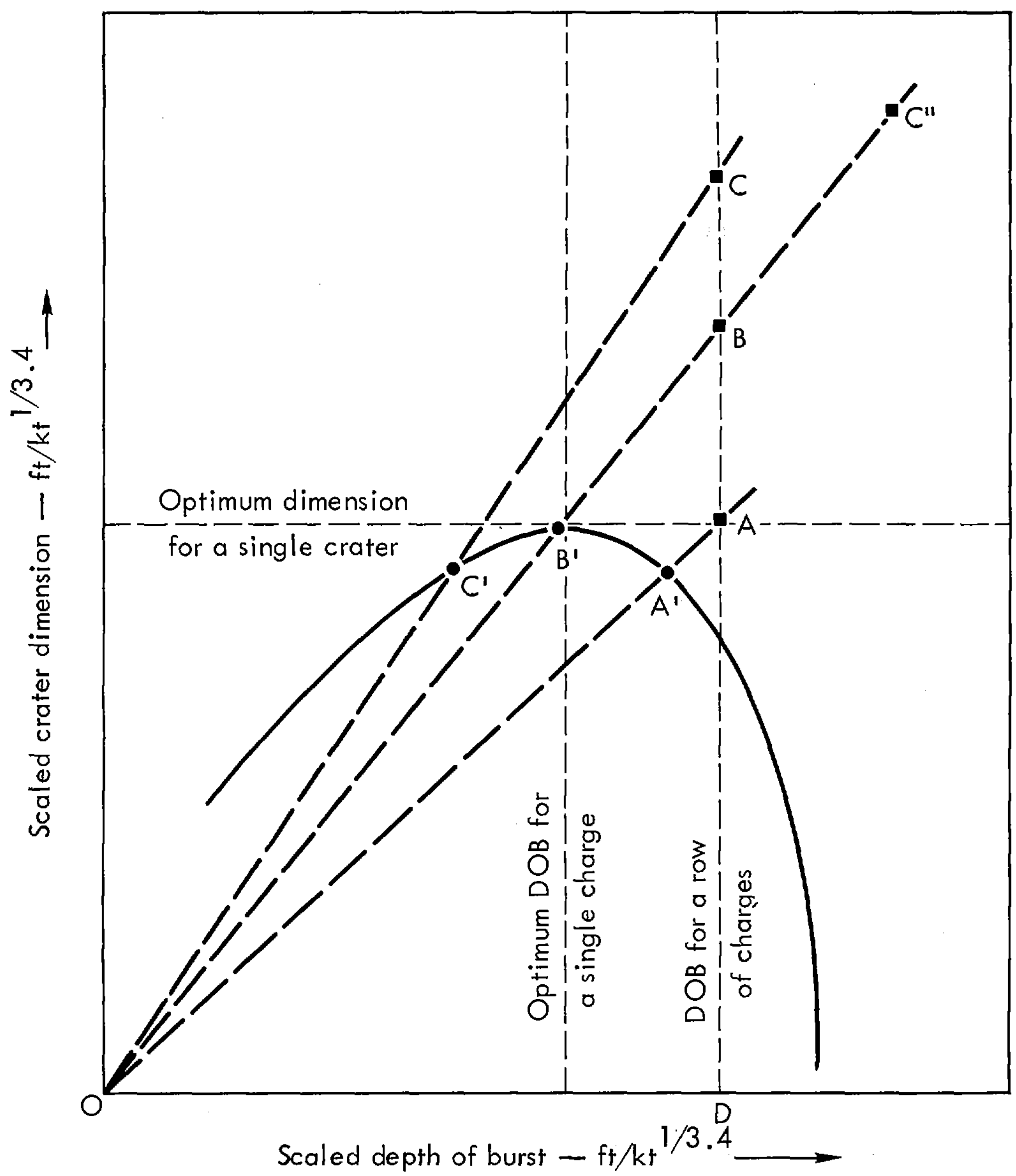

Fig. 1. Illustration of the close-spacing concept. The solid line is a typical single-charge cratering curve.

B. Consequences of Close Spacing in Interoceanic-Canal Studies

The impact of various degrees of row-charge enhancement is shown in Fig. 2. This graph shows the required yield of a single charge in a row of charges to produce a 1000-ft by 60-ft "navigation prism" at sea level for various heights of cut. Also shown is a similar curve used in the 1964 interoceanic-canal study in which no enhancement was assumed.[8]

The 1964 study assumed scaled dimensions of 140 ft/kt$^{1/3.4}$ for the crater radius and 80 ft/kt$^{1/3.4}$ for the crater depth.[8] These are the scaled Danny Boy[9] dimensions—the only data for nuclear detonations in hard, dry rock available at this time. A parabolic cross section for the crater was used in the 1964 study rather than the hyperbolic cross section used in a study just completed. The difference in crater shape has a large effect on

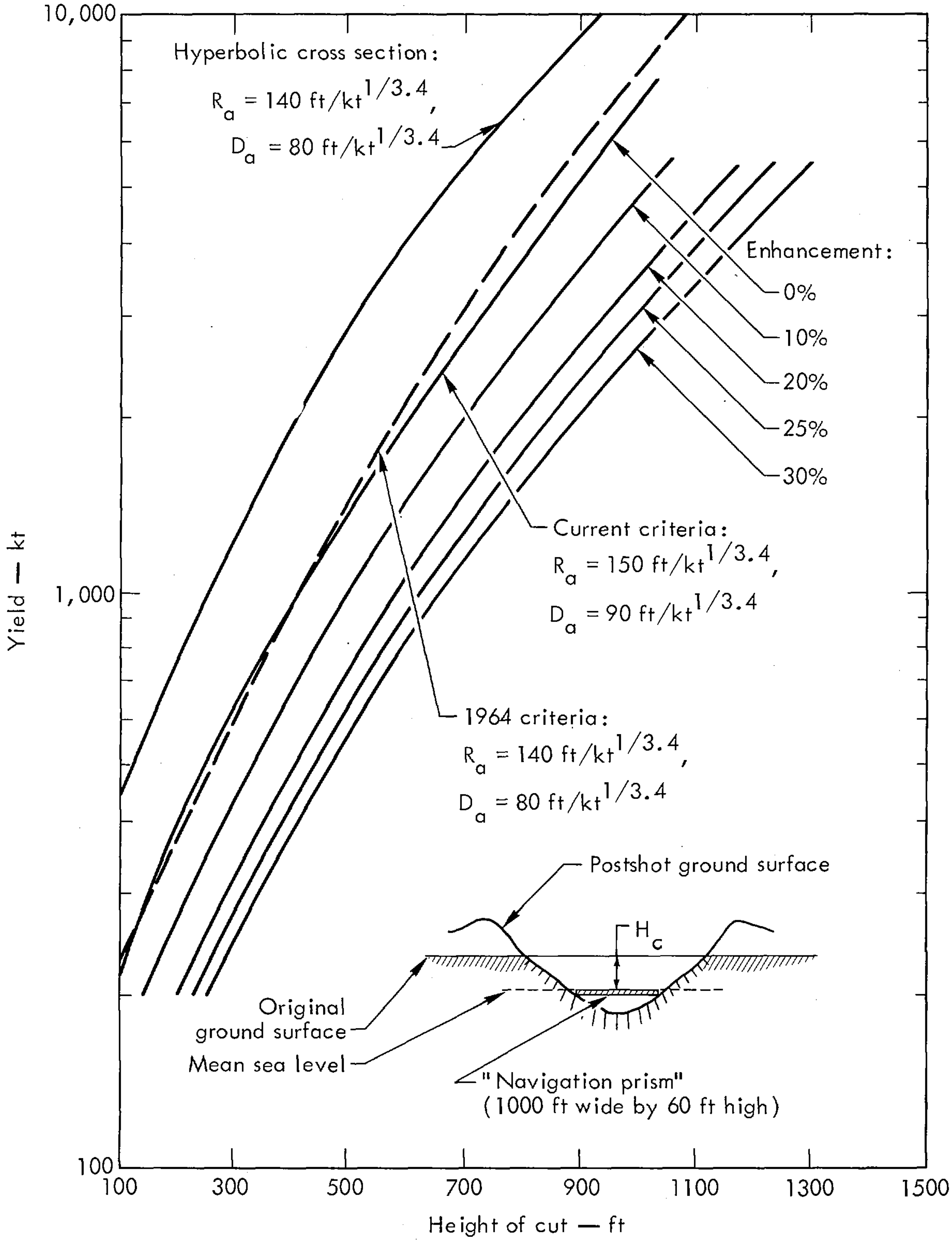

Fig. 2. Required yield of a single charge in a row of charges versus height of cut for a 1000-ft by 60-ft "navigation prism" at mean sea level (H_c = height of cut, R_a = apparent-crater radius, and D_a = apparent-crater depth).

yield requirements. The top curve in Fig. 2 shows what the yield requirements would have been in the 1964 study if a hyperbolic cross section had been used. The recent Cabriolet and Schooner experiments at a somewhat shallower depth of burst than Danny Boy lead to the conclusion that scaled single-charge dimensions of 150 ft/kt$^{1/3.4}$ and 90 ft/kt$^{1/3.4}$ for the crater radius and depth are more appropriate.

In the current study, a yield of 5.5 Mt per explosive would be required for a height of cut of 900 ft if there were no enhancement of row-crater dimensions. At 25% enhancement, the yield drops to 2.5 Mt per explosive, with a minimum of five explosives per salvo needed to satisfy the criteria that the length of the row of craters be at least twice the width. In the 1964 study, the single-explosive yield was set at 10 Mt, although the height-of-cut curve indicates that a 6.0-Mt explosive would have been sufficient. The reason for this is that the next higher yield had to be used in the family of explosive yields available at that time: 0.1, 0.2, 0.5, 1.0, 2.0, 5.0, and 10 Mt. A large fraction of the total yield required by the 1964 study stemmed from the large gaps in available explosive yields. Now, however, the current excavation-explosive design permits yield steps of 0.1, 0.2, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0, 2.5, and 3.0 Mt. This family of yields has been incorporated in the current study. No need is seen for a single-explosive yield of more than 3.0 Mt,for this will cut through elevations of more than 1000 ft if the single-charge dimensions are appropriately enhanced.

Table I and II provide a comparison of the 1964 and current studies of Route 17A in Panama and Route 25E in Colombia. The 1964 study has been modified so that the lengths of nuclear excavation proposed in that study are comparable to the lengths proposed in the current study. Most of Route 25E and all of Route 17A were considered suitable for nuclear excavation in 1964, so the number of explosives and the total yield reported in the 1964 study are much larger than the totals shown in Tables I and II.

Table I. Comparison of 1964 study (modified for length) and current study of Route 17A in Panama.[a]

1964 study			Current study		
Salvo No.	Number of explosives	Salvo yield (Mt)	Salvo No.	Number of explosives	Salvo yield (Mt)
1	18	9.0	1	16	5.0
2	31	9.2	2	16	4.5
3	10	5.0	3	5	5.5
4	14	10.0	4	13	4.3
5	10	9.5	5	12	5.2
6	9	11.0	6	15	5.0
7	10	12.0	7	8	4.9
8	4	3.5	8	9	4.9
9	9	10.0	9	9	5.1
10	30	10.2	10	8	5.6
			11	5	5.2
			12	8	5.0
			13	7	5.8
			14	7	7.1
			15	5	11.0
			16	7	4.9
			17	7	6.5
			18	7	4.9
			19	14	2.8
Total	145	120.9		178	103.2

[a]Requirements for the main navigation channel only. Additional explosives and salvos are provided for river diversions.

Table II. Comparison of 1964 study (modified for length) and current study of Route 25E in Colombia.[a]

1964 study			Current study		
Salvo No.	Number of explosives	Salvo yield (Mt)	Salvo No.	Number of explosives	Salvo yield (Mt)
1	19	12.6	1	10	5.3
2	6	13.0	2	12	5.2
3	4	35.0	3	7	5.3
4	4	30.0	4	5	5.6
5	4	11.0	5	5	13.0
6	10	9.5	6	5	9.5
7	6	9.0	7	7	5.4
8	7	10.0	8	7	6.4
9	4	10.0	9	9	4.7
10	4	10.0	10	5	3.9
11	4	17.0	11	5	5.9
12	4	14.0	12	5	5.4
13	4	11.0	13	5	6.5
14	4	14.0	14	5	9.0
15	9	10.0	15	6	5.4
16	17	10.0	16	8	4.0
17	10	5.0	17	9	5.1
Total	120	231.1		115	105.6

[a]Requirements for the main navigation channel only. Additional explosives and salvos are provided for river diversions.

For Route 17A (Table I), the most significant change is the reduction of the 35-Mt salvo yield in the 1964 study to a maximum of 11 Mt in the current study. The remaining salvo yields could have been reduced to about 5 Mt by reducing the number of explosives in each salvo and increasing the number of salvos. For Route 25E (Table II), there is a tremendous improvement over the 1964 plan. The total yield has been reduced by more than a factor of 2 while retaining about the same number of explosives. In contrast to Route 17A, only a few salvos could have been reduced to 5 Mt on Route 25E because the average elevation of the nuclear portion of Route 25E is much higher than that of Route 17A. The need for additional explosives in the close-spacing concept is somewhat compensated for in the current study by the use of spacings 15% larger than those assumed in the 1964 study in salvos for which the yield is not critical.

An important factor that has not been included in the current study and that could lead to still further reductions in yield is the difference in cratering characteristics between the kinds of rock found along the canal routes and the dry, hard rock at the Nevada Test Site on which both studies are based. The canal rocks are saturated with water, making them weaker, and the increased water vapor leads to a stronger gas-acceleration phase in the cratering process. The scaled crater dimensions for saturated rocks are therefore expected to be larger than those for dry rocks. Cratering calculations employing LRL's TENSOR code and an equation of state derived from rock samples along both routes indicate that crater dimensions at the megaton level may be 10 to 15% larger than those assumed in the current study.[10] A 10% increase in crater dimensions would reduce yield requirements by about one-third.

1. Seismic Motion

At the time of the 1964 study, ground-motion data were quite limited, for the largest single contained explosion up to that time was about 200 kt and no damage from nuclear detonations had occurred. Subsequent information obtained from explosions at the megaton level and from low-yield detonations away from NTS and close to populated areas pointed out the need to reduce the salvo yields presented in the 1964 study. A significant finding was that complaints were received for minor architectural damage, such as hairline cracks in masonry structures, at very low levels of ground motion. Although such damage is a nuisance and does not affect the structural integrity of a building, the payment for such damage could be an important economic factor in nuclear excavation.

Figure 3 summarizes experience to date on complaints of architectural damage versus pseudo absolute acceleration. Pseudo absolute acceleration is the calculated response of a structure (treated as a single-degree-of-freedom system) to the actual ground acceleration. Although Fig. 3 shows that complaints have been received for motions as low as 3 cm/sec^2, damage complaints have generally not been recognized as valid below about 40 cm/sec^2.

Table III compares the pseudo absolute accelerations expected for the closest large cities to Routes 17A and 25E at several yields. These values are shown for comparative purposes only since recent improvements in predictive techniques indicate that these accelerations will actually be lower than indicated.

Table III. Seismic motions expected in the closest large cities to the proposed canal routes.[a]

City	Distance from closest detonation (km)	Yield (Mt)	Expected pseudo absolute acceleration[b] (cm/sec^2)
Route 17A			
Panama City, Panama	180	35	63
		11	30
		5	18
Route 25E			
Medellin, Colombia	230	35	53
		13	27
		5	15

[a]Taken from Ref. 12.

[b]These values are applicable only to buildings that are less than five stories high.

Much higher levels of motion will be experienced closer to the nuclear detonations. In the current study it is assumed that all nonproject personnel will be evacuated from areas in which the ground acceleration is expected to be 0.3 g or higher. Between 0.3 and 0.1 g, special precautions will be needed to avoid possible injury. A possible precaution would be to have people stand outdoors away from buildings so that loose objects will not fall on them.

High-rise structures respond differently to ground motions than low structures do. A plot similar to Fig. 3 is not available for high-rise

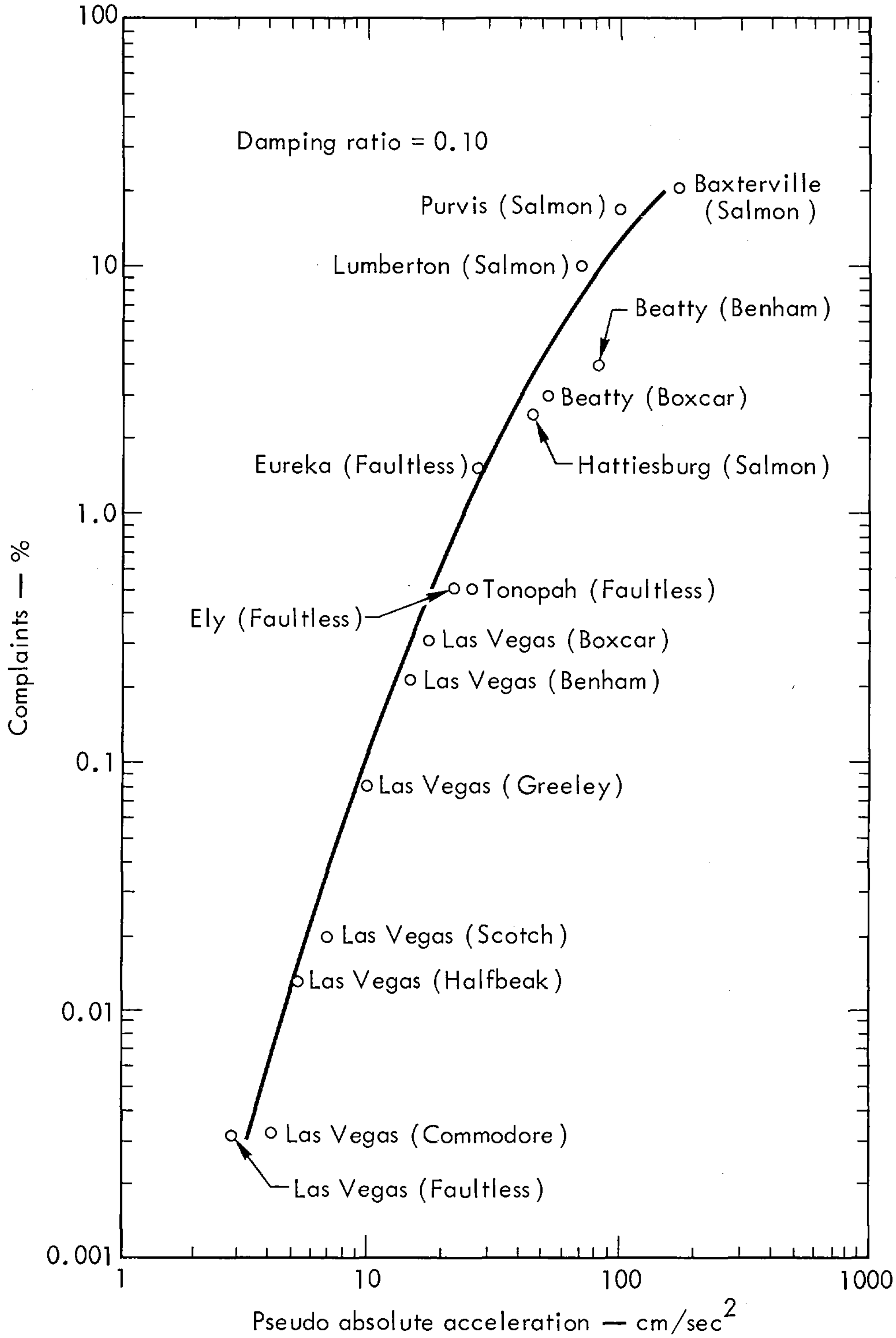

Fig. 3. Relationship between pseudo absolute acceleration and complaints of architectural damage for eight nuclear events: Salmon (Mississippi), Faultless (central Nevada), Commodore (Yucca Flat), and Boxcar, Benham, Greeley, Halfbeak, and Scotch (Pahute Mesa). Values for the ordinate are derived by dividing the total number of complaints from a given town by the total number of structures in that town and then multiplying by 100. Taken from Ref. 11.

structures because no damage to such buildings has occurred as a result of nuclear testing. The largest motions to which high-rise buildings in Las Vegas have been subjected so far resulted from a 1.2-Mt detonation (Boxcar). At a period of 1 sec (the natural response of tall buildings is between 1.0 and 5.0 sec), the pseudo relative velocity of the upper stories was about 3 cm/sec, which corresponds to a pseudo acceleration of about 20 cm/sec^2.

Additional information on high-rise structures is available from earthquakes. The Tehachapi/Bakersfield earthquake of 1952 generated motions in Los Angeles that were equivalent to those from a 20- to 30-Mt nuclear explosion at the same distance of 160 km. No structural damage to high-rise structures occurred, although many of them had been constructed prior to the establishment of rigorous building codes.[3] Pseudo response motions corresponding to velocities of about 20 cm/sec and accelerations of 50 to 100 cm/sec^2 were measured for periods between 1.0 and 2.0 sec. Figure 4 compares the velocity response of tall buildings to various seismic shocks and shows the calculated response spectrum for 5- and 10-Mt explosions at 180 km.

Techniques for predicting the response of high-rise structures to seismic motions have been developed and will continue to be improved and refined as more experimental data at high yields become available. The spectral-matrix method can provide a time history of the response of a real high-rise structure to any specified seismic wave train.[13] The accuracy of these code calculations is dependent on the data available for the design and construction of the real building and on the accuracy of the predicted ground-motion history.

A difficulty that is encountered in predicting the response of a limited number of high-rise structures in Central and South America to high-yield canal detonations is that building-design data may not be available. Even when such data exists and indicates a structurally sound design, there is no assurance that the actual construction methods employed have followed the design criteria. For this reason, the detonation plans and schedules proposed for Routes 17A and 25E contain provisions for increasing salvo yields from approximately 1.0 to 3.0 Mt to 9.0 Mt. Detailed calculations, analyses, and inspection will be needed to identify individual structures that may be sensitive to the low predicted levels of ground motion. To preclude the possibility of personal injury, such buildings could be evacuated at shot time, or they could be purchased and razed. It is believed that the purchase of a limited number of buildings would not alter the economic feasibility of constructing a sea-level canal with nuclear explosives.

2. Air Blast

Although air-blast effects must be considered in any feasibility study, their impact is mainly one of operational restraint along with the associated cost of limiting detonations to only those days that have the desired meteorology. Atmospheric focusing of the acoustic wave generated by a cratering explosion could result in overpressures sufficient to break windows at ranges of several hundred kilometers. These acoustic-wave reflections are controlled by the temperatures and winds aloft.

Data collected during the site investigations for Routes 17A and 25E indicate that there is a sufficient number of days each year in which no air-blast effects would occur.[3] The proposed operational procedures would require only three or four such days during the year. The explosive packages and firing systems are capable of standing by on a ready basis for as long as six months if necessary. Four or five salvos could be detonated on any acceptable firing day at intervals of about one hour or less. Except on

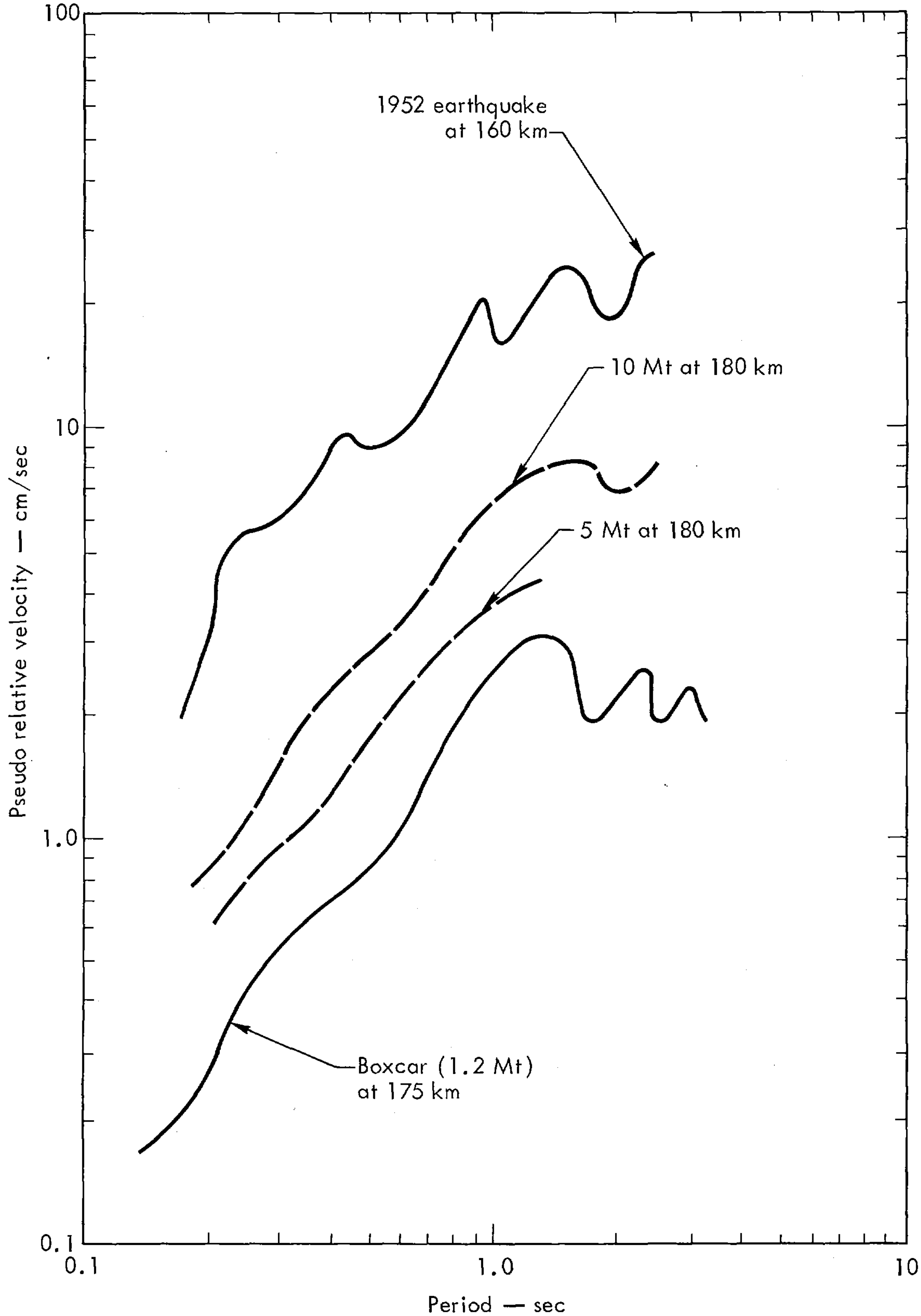

Fig. 4. Velocity response of high-rise structures to seismic shocks. The two dashed curves are calculated. Taken from Ref. 3.

the actual detonation day, construction operations such as emplacement-hole drilling and emplacement of explosives would continue in a normal fashion during the waiting period.

Direct air blasts at close ranges are not particularly affected by meteorological conditions. They can be controlled only by assuring that the evacuation area is sufficiently large to preclude personal injury from breaking glass.

3. Radioactivity

LRL is continuing to improve the design of a nuclear excavation explosive so that less fission- and neutron-induced radioactivity is produced. However, no matter how much the explosive design is improved, radioactivity will still be produced and precautionary measures will still need to be taken. The main result of improving an explosive design over that assumed in the current study would be to reduce the size of the evacuation area needed to contain the local fallout to within safe levels. The infinite-dose contour of 0.34 R, which is based on the explosive design used in the current study, is almost contained within the evacuation areas required for seismic safety (0.3 g) around Routes 17A and 25E. People residing outside the 0.34-R contour would receive an external exposure of less than 340 mR in a lifetime, or a small fraction of the total exposure of about 10,000 mR in a lifetime due to natural background radiation. Internal exposures derived from radioactivity concentrated in food chains do not appear to be significant outside the 0.34-R contour.[14] Provisions are made for continuously monitoring foodstuffs to ensure that human exposure is well below recommended guidelines. In a practical sense, the evacuation area will be significantly larger than the 0.34-R contour. For control purposes, the area will be extended to include natural barriers such as rivers or mountain ridges.

HARBOR CONSTRUCTION

The use of nuclear explosives to construct deep-water harbors is probably the most straightforward application of nuclear excavation at this time since the degree of accuracy required in the crater dimensions is not expected to be critical. The ground surface will generally be at about sea level, and salvo yields can be kept quite low. Because of the low elevations, row-charge enhancement is not a factor in harbor design, and in fact is undesirable. The spacing between explosives should be as wide as possible in order to optimize the harbor area and minimize the harbor depths created by each explosive. Explosives with a spacing of $1.5R_a$ would provide about 50% more surface area per explosive than explosives in a close-spaced row would (assuming 25% enhancement of crater width at a spacing of $0.8R_a$). This is illustrated by the comparison between close and wide spacing shown in Fig. 5. Figure 6 shows an idealized situation for a nuclear-excavated harbor. Even with wide spacing between 200-kt explosives, the estimated harbor depth may still be deeper than required or desired.

If a harbor is to be constructed where the ground surface is below mean low tide, several unknowns are encountered. The first unknown deals with the water waves generated by the detonation and whether hazardous conditions will be created for some distance along the shoreline. The second unknown deals with the formation of crater lips and whether they will survive the returning water waves. The third unknown concerns the nature of the fallback material and whether significant changes in the crater shape should be expected if the fallback material is entrained in sufficient water to liquefy or "quicken" it upon deposition.

It is believed that the generation of water waves can be quantitatively determined analytically, and LRL is currently studying this problem. It is unlikely that the generation of water waves will seriously affect this proposed application, although it must be considered in any safety analysis.

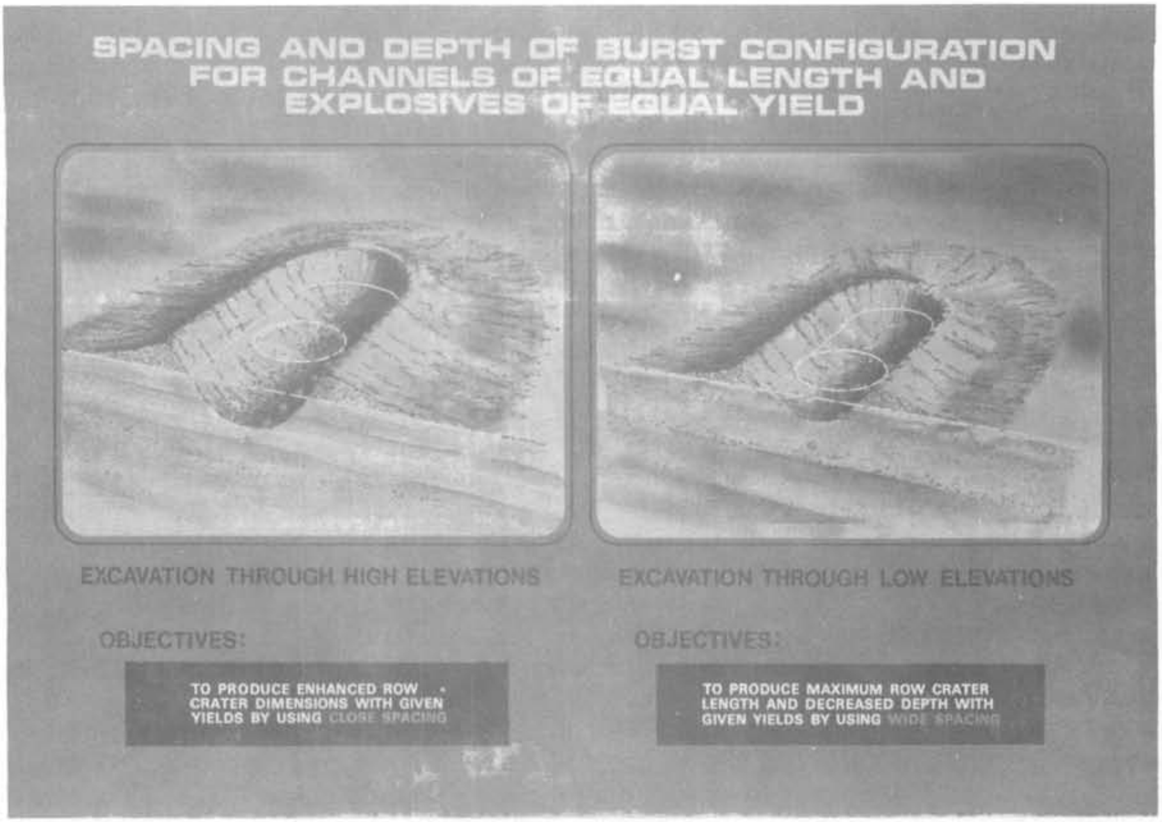

Fig. 5. Illustration of row-charge excavation—close versus wide spacing between explosives.

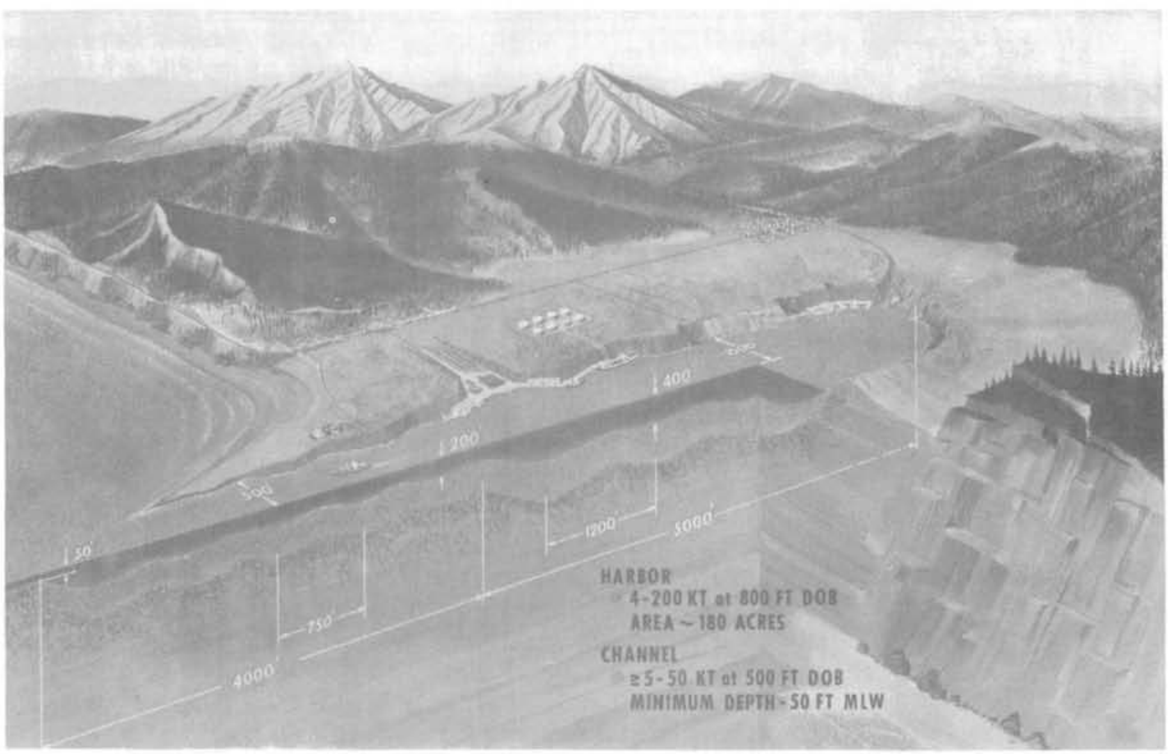

Fig. 6. Idealized plan for excavating a harbor with nuclear explosives.

The questions of lip formation and crater shape are much more difficult to resolve analytically, and experiments are needed. Some preliminary information is available from the calibration charges fired as a prelude to Project Tugboat, a chemical-explosive experiment designed to produce a shallow harbor for small boats at Kawaihae, Hawaii.[15] Five cratering charges produced no lips at all and very broad, shallow craters.[16] If crater lips were initially formed, they and most of the ejecta material were subsequently washed back into the craters by the returning water waves. The cratered material consisted of a low-strength, high-porosity coral, and the apparent crater was probably due entirely to compaction. With mean low tide as the reference plane, the water overburden probably ranged between 12 and 20% of the total depth of burst.

If crater lips are essential as a breakwater for a nuclear-excavated harbor, it is clear that the geology of the site is a critical factor. The upthrust portion of a crater lip in hard, competent rock is most likely to survive the turbulence of returning water waves. Where less competent rock exists, the yield requirements for a harbor may be dictated by the height required for the upthrust lip. In the Danny Boy experiment (0.42 kt at a depth of burst of 110 ft), about 14.5 ft of the average lip height of 24 ft was the result of upthrust.[17] For 100 kt in similar relatively incompactible rock, the upthrust portion of the lip height would be expected to be about 75 ft, assuming that lip heights can be scaled according to $W^{1/3.4}$, where W is the explosive yield. The lack of nuclear-cratering experiments in rock formations having the same equation of state precludes a definitive empirical relationship. In compactible rock (low strength and high porosity), permanent displacement of the ground surface is greatly reduced since the initial cavity that forms during the detonation continues to expand mainly by compaction of the surrounding medium rather than by displacement.

Geology similar to that encountered in the Schooner experiment[18] (31 kt at a depth of burst of 355 ft) might possibly be suitable, but the yield requirements would be dictated by the upthrust required. The Schooner lip height averaged only 44 ft, of which probably only about 25 to 30 ft was upthrust. Since the yield of Schooner is a factor of about 75 larger than Danny Boy, these dimensions are small in comparison to the 14.5 ft of upthrust measured in Danny Boy. Some of this difference can be attributed to the difference between the scaled depths of burst (deeper cratering charges produce greater upthrust), but geology is the major factor. The Danny Boy basalt is a dense, competent rock from the detonation point to the ground surface. For Schooner, the rock from the ground surface to a depth of 120 ft is a dense, competent welded tuff. From 120 to 337 ft (near the detonation point), the rock is very weak, highly porous, and has a density between 1.25 and 1.5 g/cc. A single-charge yield of about 1.0 Mt would be required to produce an upthrust height of about 75 ft in Schooner-like rock as compared to the 100 kt required for dense rock.

The change in crater shape that results when the fallback material acts like a fluid upon deposition can be quite easily estimated from existing data. Crater widths would not be affected, but crater depths would be significantly reduced. The resulting crater shape would be more ideal for a harbor than the expected hyperbolic cross section. As an example, a cross section of the Schooner crater is compared in Fig. 7 with the shape that would have resulted if all the fallback material had been in a fluid state. The size and shape of the true crater, then, determines the resulting apparent crater. The volume of the fallback material is determined from the difference between the volume of the true crater and that of the apparent crater. The volume and approximate shape of the true crater are estimated from TENSOR calculations for the Schooner experiment.[18] The volume of the apparent crater has been measured by aerial survey. If ejecta material were to be

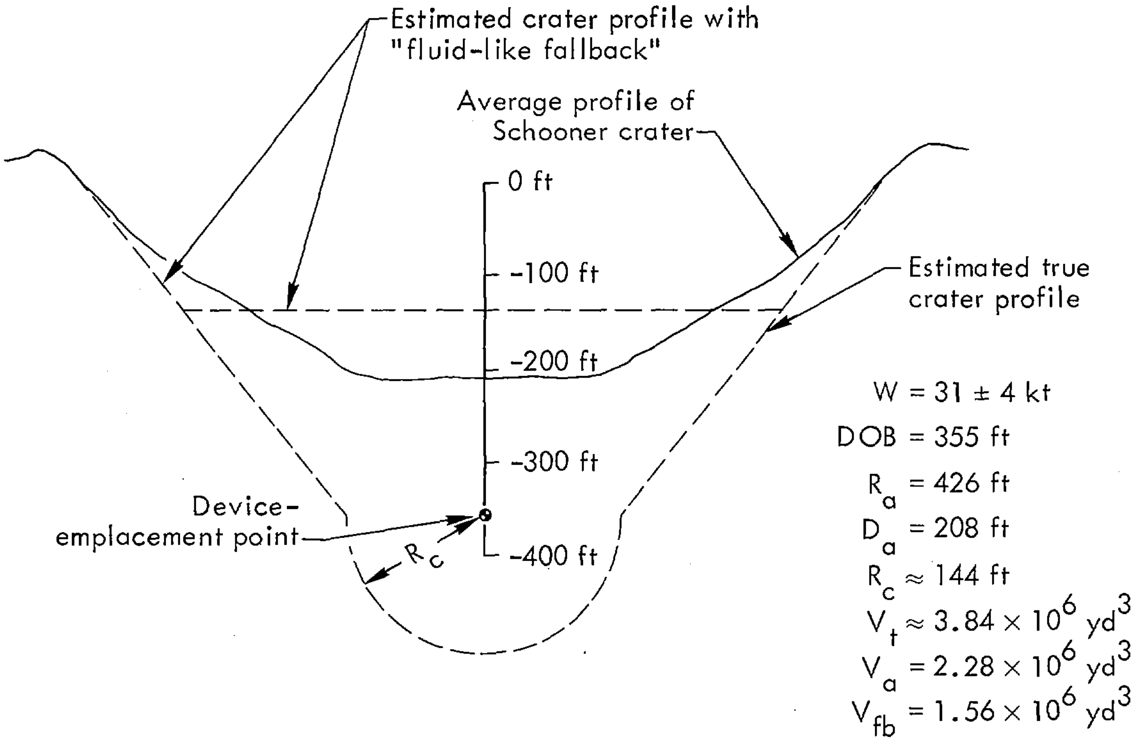

Fig. 7. Estimated changes in the shape of the Schooner crater that would have occurred if the fallback had had fluid properties (W = yield, DOB = depth of burst, R_a = apparent-crater radius, D_a = apparent-crater depth, R_c = cavity radius, V_t = true-crater volume, V_a = apparent-crater volume, and V_{fb} = fallback volume).

washed back into the crater, the depth would become even shallower. It is unlikely that analytical techniques for determining the volume of "washback" material can be developed because of the large number of variables and unknowns involved. A demonstration at full yield would be required.

A. Cape Keraudren Harbor

A proposed harbor-excavation project at Cape Keraudren, Australia, was studied in some detail in 1968.[19] The specific site and plan were developed in response to a request from a major shipping firm. An agreement could not be reached with potential buyers on the cost of the ore that was to be shipped out of Cape Keraudren, so the shipping firm was forced to withdraw its proposal. The Australian Atomic Energy Commission has shown considerable interest in harbor excavation and is continuing to study alternative locations. Exploitation of the vast ore deposits in northwestern Australia requires deep-water harbors from which the ore can be shipped to countries like Japan.

The sea bottom along the coast of northwestern Australia generally slopes downward at a rate of less than 10 ft/mile. At Cape Keraudren, vessels with a 60-ft draft can approach only to within 4 miles of the shoreline at high tide, which has a range of 25 ft.

The harbor plan provided for the simultaneous detonation of five 200-kt explosives spaced 1100 ft apart and buried at about 750 ft. The harbor thus produced was to be about 6000 ft long, 1600 ft wide, and 200 to 400 ft deep. The total lip heights were estimated to be 200 to 300 ft on the sides and 30 to 60 ft on the ends. An artist's conception of the harbor is shown in Fig. 8. The harbor was designed to handle ore carriers of 100,000 to 147,000 tons deadweight and the following approximate dimensions: length, 1000 ft; beam, 135 ft; and draft, 60 ft. Two alternatives were considered—one that would tie the end of the row crater to the shoreline, and one that would place the row crater about 7500 ft off-shore to reduce the amount of conventional dredging required to provide access to the open sea. A causeway was to tie the off-shore harbor to the shoreline.

Fig. 8. Plan for excavating a harbor at Cape Keraudren, Australia.

For the off-shore harbor, the sea bottom is about 20 to 24 ft below mean low tide. Little information is available concerning the geology of this site, and that only to a depth of 100 ft. Up to 13 ft of silty sand on the ocean bottom is underlain by a layer of hard-to-soft limestone with a known thickness of 18 to 32 ft. The limestone increases in thickness toward the shore and emerges as 20- to 25-ft-high cliffs at Cape Keraudren. The limestone is underlain by an unknown thickness of interbedded quartz sand, clay, and sandstone. Additional geologic investigations would be required to establish the suitability of this site.

A preliminary safety analysis based on a limited amount of site data revealed no major deterrent to pursuing further detailed investigations and analyses.

It would appear that construction of a relatively-low-cost harbor (less than $20 million) would be a reasonable first step in demonstrating the usefulness of nuclear excavation as an engineering tool. The tremendous amount of information that would be obtained is directly applicable to much larger projects such as an interoceanic canal, and would provide a real basis for comparing conventional versus nuclear excavation.

HIGHWAY CUTS

A number of potential projects involve cutting passes through mountain ranges for highways and railroads to reduce distances and grades. In most cases, such massive cuts would not even be considered with conventional excavation because of the high cost and the long period of construction time required. Conventional excavation becomes more competitive as the height of cut is reduced, and in general, nuclear excavation would not be considered for cuts of less than 100 ft.

Of all the excavation applications proposed, a highway cut requires the highest degree of accuracy in the prediction of crater dimensions, for either over- or under-excavation requires correction by conventional methods. The elevation of the bottom of the row crater and the uniformity of that elevation are the features that must be predicted accurately. Crater depths, however, are the most difficult parameter to predict at optimum and deeper-than-optimum depths of burst where a significant amount of fallback material is involved. At such depths of burst, the depth of the apparent crater is sensitive not only to the size of the true crater and the volume of the fallback material, but also to the bulking factor of the fallback material and to the fallback's angle of repose with dynamic placement. A bulking factor is the ratio of the in-situ rock density to the bulk density of the fallback or ejecta. Cratering calculations with the TENSOR code can be used to determine the size of the true crater and the volume of the fallback material,[20] but there is no similar analytical technique that can start with an in-situ rock formation, predict the particle-size distribution resulting from the cratering process, and determine the changes in crater shape caused by the dynamic compaction that derives from the kinetic energy of the fallback material.

The bulking factors of the fallback material in the nuclear cratering experiments conducted to date can be estimated quite easily, but the degree of accuracy is unknown. The verification of bulking factors and representative particle-size distributions requires extensive and expensive postshot investigations. However, Table IV summarizes the dimensions and volumes of three nuclear cratering experiments (Danny Boy, Cabriolet, and Schooner) and shows a calculated value for the bulking factor. Although the estimated bulking factor is smallest for the highest explosive yield, the differences in the characteristics of the three kinds of rock involved may be the most important factor. Information from contained experiments indicates a trend toward lower bulking factors at higher yields.

Figure 9 uses the Danny Boy crater to show the estimated effect on crater shape and depth of changes in the bulking factor. At 80 and 70% of the original bulking factor of the fallback material, the crater depths would increase by about 8 and 16% respectively. Hence, uncertainties in crater depths are reduced in excavations that take place in materials and at yields that produce low bulking factors.

Crater depths would be most predictable at relatively shallow depths of burst in which the shot points are exposed. However, the amount of radioactivity released would be considerably greater than that at optimum depths of burst and would be about a factor of 2 greater than that assumed per explosive in the canal safety analysis. The basic mechanisms that control the release of radioactivity in cratering events are still not well known, but studies are continuing.

Table IV. Summary of nuclear-crater dimensions and estimated bulking factors.

Event	Kind of rock	Yield (kt)	Depth of burst (ft)	R_c [a] (ft)	R_a [b] (ft)	D_a [c] (ft)	V_t [d] (10^4 yd^3)	V_c [e] (10^4 yd^3)	V_a [f] (10^4 yd^3)	V_ℓ [g] (10^4 yd^3)	V_{up} [h] (10^4 yd^3)	V_{fb} [i] (10^4 yd^3)	V_e [j] (10^4 yd^3)	Bulking factor [k]
Danny Boy	Basalt	0.42	110	37	107	62	7.7	0.78	3.6	8.0	2.4	4.1	5.6	1.33
Cabriolet	Trachyte	2.3	170	75	181	117	37	6.5	18	24.2	6.5	19	17.7	1.09
Schooner	Tuff	31	355	144	426	208	384	47	228	275	47	156	228	1.06

[a] R_c = cavity radius; value for Danny Boy measured,[21] values for Cabriolet and Schooner taken from TENSOR calculations.[18,22]

[b] R_a = apparent-crater radius; all values measured.[23]

[c] D_a = apparent-crater depth; all values measured.[23]

[d] V_t = true-crater value; all values calculated by $V_t = (\pi/3)\mathrm{DOB}\left(R_a^2 + R_c^2 + R_a R_c\right) + (2/3)\pi R_c^3$.

[e] V_c = volume of initial cavity around detonation point; all values calculated by $V_c = (4/3)\pi R_c^3$.

[f] V_a = apparent-crater volume; all values measured.[23]

[g] V_ℓ = apparent-lip volume; all values measured.[23]

[h] V_{up} = true-lip volume (upthrust); value for Danny Boy measured,[24] values for Cabriolet and Schooner arbitrarily assumed to be equal to V_c

[i] V_{fb} = fallback volume; all values calculated by $V_{fb} = V_t - V_a$.

[j] V_e = ejecta volume; all values calculated by $V_e = V_{al} - V_{tl}$.

[k] All values calculated by $BF = (V_e + V_{fb})/[V_t - (V_c/2)]$. Measured bulking factors in the Danny Boy lip in two trenches were 1.44 and 1.19.[17] A measured bulking factor in the Cabriolet lip ranged from 1.11 to 1.16.[25]

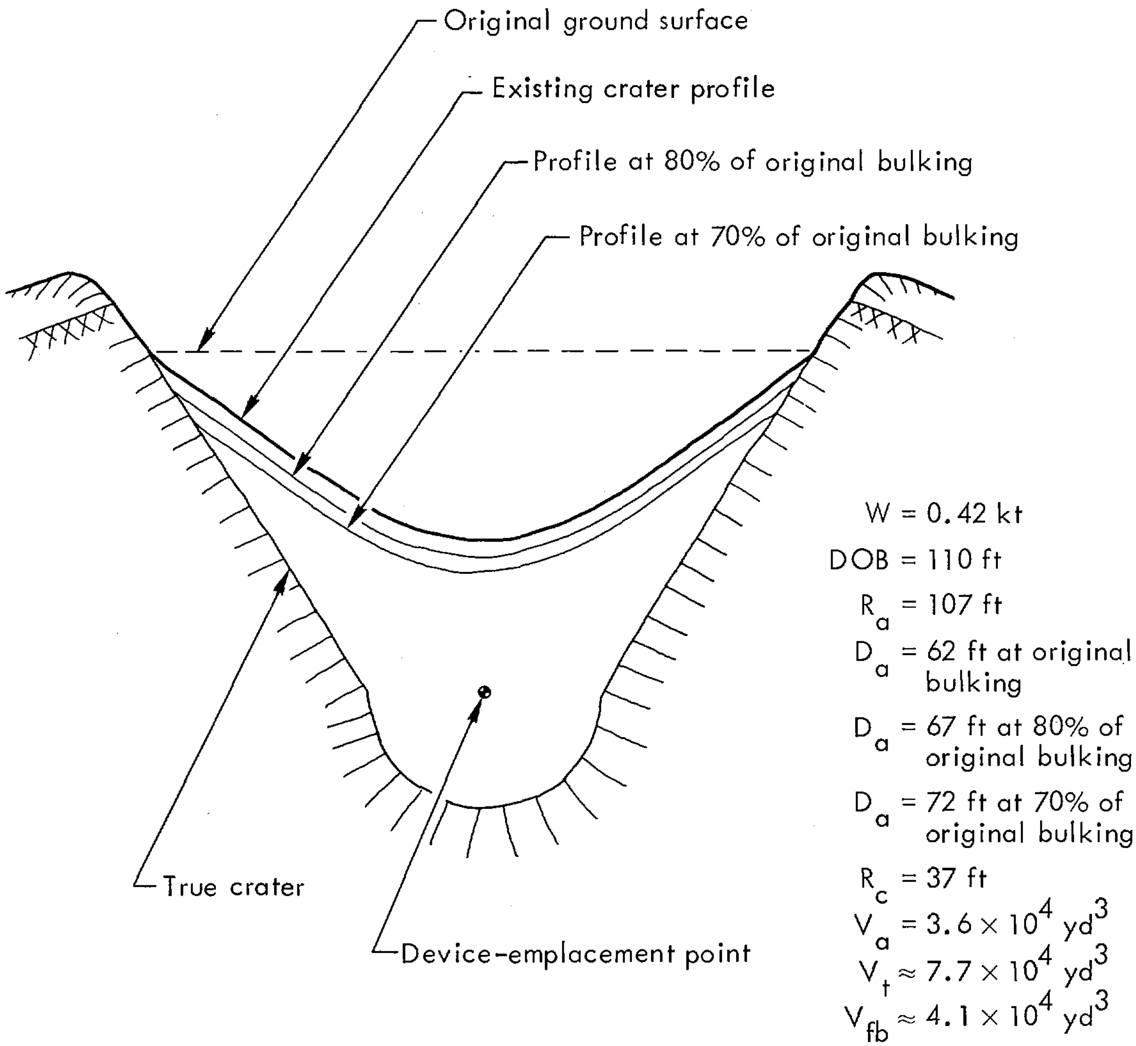

Fig. 9. Estimated changes in the shape of the Danny Boy crater that would have occurred at different bulking factors of the fallback material (W = yield, DOB = depth of burst, R_a = apparent-crater radius, D_a = apparent-crater depth, R_c = cavity radius, V_t = true-crater volume, V_a = apparent-crater volume, and V_{fb} = fallback volume).

Highway cuts that must be made with more than one salvo because of yield limitations imposed by the projected seismic motion pose another problem. The connection of row charges results in the preferential ejection of some material into the previously excavated row. The amount of the material and its distribution within the adjoining crater is difficult to predict. Some experimental data are available for row-charge connections with chemical explosives at the 1- to 30-ton level, but these data cannot be directly applied to nuclear explosives at the 100-kt level. A mathematical model for this directed-explosion effect would require a three-dimensional code that does not exist and that may be impractical to develop. Simplifications may be possible to allow calculation with the two-dimensional TENSOR code, but verification will need to be obtained experimentally. The problem of row-charge connections is not as critical in a sea-level canal because it appears that there is sufficient volume below the navigation prism to accept the ejecta.

A. Project Carryall

Project Carryall is the name given to a proposed nuclear cut in the Bristol Mountains near Amboy in southern California. The cut was to be used for an interstate highway and a railroad. A feasibility study by the California State Division of Highways, the Atchison, Topeka, and Santa Fe Railway Company, the Lawrence Radiation Laboratory, and the U.S. Atomic Energy Commission was completed in 1964. The study concluded that the

Fig. 10. Model of the proposed Carryall project.

project appeared to be technically feasible providing that nuclear row-cratering experiments were first conducted at NTS.[26] The study also concluded that the nuclear solution was $8,000,000 cheaper than the conventional solution, not counting the cost of the nuclear explosives. This project did not proceed beyond the feasibility study primarily because the time required to execute the requisite experiments at NTS was not compatible with the deadline for completing the interstate highway system.

Figure 10 shows a model of the proposed project. A conventional cut through this portion of the Bristol Mountains was deemed to be economically impractical. The proposed realignment, however, would have shortened the railway by 15 miles and saved 50 min of freight-train time.

The nuclear cut was to be about 2 miles long and was estimated to require a total yield of 1.83 Mt from 23 explosives. The largest single-explosive yield was 200 kt. The height of cut varied from 100 to 340 ft. As can be seen in Fig. 10, the excavation was slightly curved to avoid higher cut elevations. The only advantage to incorporating the close-spacing concept in the Carryall plan would be to allow the alignment to be straightened by going through higher elevations with no increase in explosive yields. With 25% enhancement of single-crater dimensions, 100 kt would be sufficient for a height of cut of 435 ft and 200 kt would be sufficient for 535 ft.

An interesting feature of the Carryall project was the use of a single 100-kt crater to solve a drainage problem. The volume of this crater would hold the maximum possible flood of 850 acre-ft expected in the nearby Orange Blossom Wash. This water would otherwise flow into the cut. The water trapped in such a crater would be dissipated by evaporation and some seepage. The conventional solution would have required the construction of threebridges, a channel, a dike, and riprap for slope protection.

NUCLEAR QUARRIES

A retarc (rubble mound) generated by a nuclear explosive at a depth much deeper than optimum for cratering in hard rock is potentially one of the most useful nuclear-excavation applications suitable for employment within the continental United States. In addition to producing large volumes of broken rock economically when placed close to the area of utilization,[27] the retarc can also be used as a dam. The major advantages of the retarc in comparison to craters include a much smaller release of radioactivity and the fact that relatively small yields produce a sufficient amount of broken rock to construct very large structures such as rock-fill dams.

The Sulky experiment (0.085 kt at a depth of burst of 90 ft; see Figs. 11 and 12) is the model on which potential nuclear-quarry applications are based. A practical concept of a nuclear quarry is shown in Fig. 13. Here, the detonation takes place on a hillside so that the rock within the true crater is more readily accessible to loading equipment.

Knowledge of the fragment-size distribution is an important consideration for most nuclear-quarry applications. The distribution of preshot fractures, including the development of joint sets, is probably the most important single factor determining the final size distribution of explosion-broken rock.[17,27] No data are available for the fragment-size distribution resulting from a nuclear explosion in a massive rock formation where the existing fractures and joint sets are widely spaced. The economics of a nuclear quarry could be altered if a significant amount of secondary blasting is required to reduce large blocks to manageable and useful dimensions.

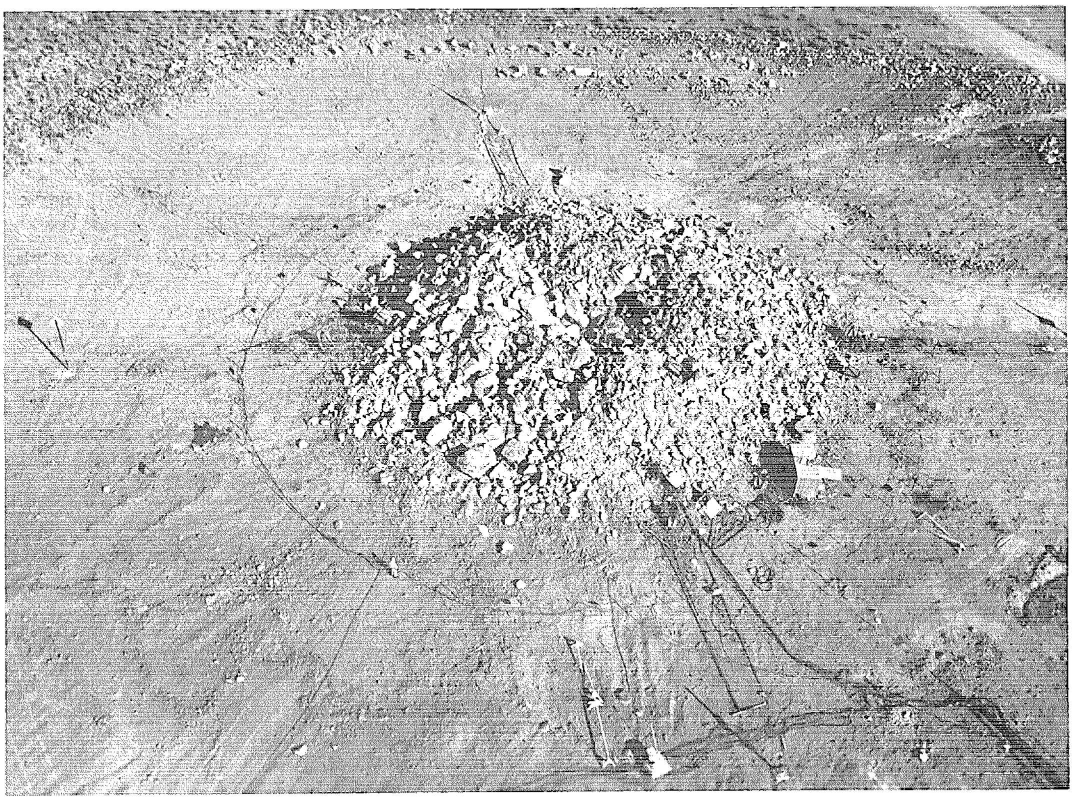

Fig. 11. Aerial view of the Sulky retarc.

Fig. 12. Edge of the rubble mound formed by the Sulky experiment.

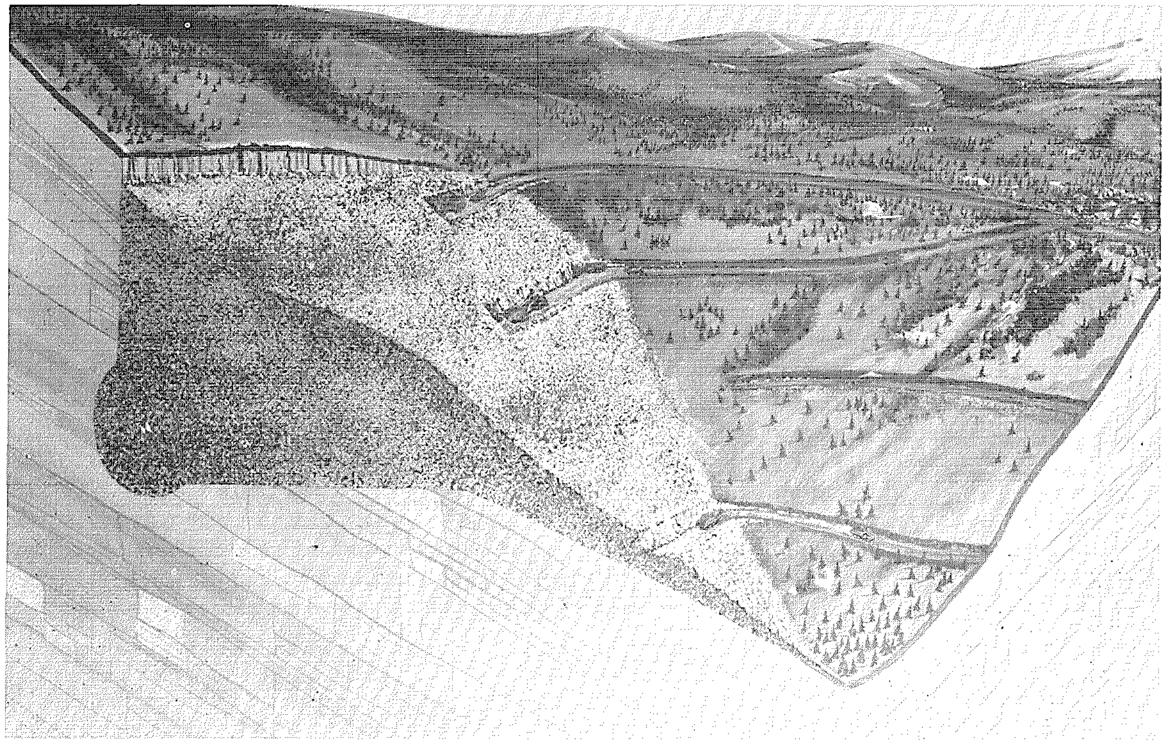

Fig. 13. Illustration of the nuclear-quarry concept.

The size of the evacuation area for a nuclear-quarry detonation is determined primarily by seismic considerations. Only a small amount of radioactivity would be vented to the atmosphere, and most of that is gaseous and does not result in fallout. The radioactivity produced is mixed and diluted into the large volume of broken rock at low levels. With a thermonuclear explosive, the isotope of primary concern is tritium in the form of THO. The rock aggregate can be washed prior to use and the wash water controlled and disposed of in a safe manner. Depending on the site and its geohydrologic characteristics, precautions may be necessary to preclude uncontrolled leaching of the tritium or other radionuclides from the retarc rubble.

A. Project Travois

Project Travois is a joint experiment of the AEC and the Corps of Engineers to demonstrate the nuclear-quarry application. Studies conducted by the Corps of Engineers produced three possibilities involving the production of quarry rock for rock-fill dams. The Twin Springs Dam Project near Boise, Idaho, was ultimately selected as the most promising site for an experiment. Preliminary site investigations conducted by the Corps of Engineers indicate that the rock there is suitable for a nuclear quarry, and a savings of about $1,000,000 is estimated in comparison with the conventional solution.[28] This savings does not include the expanded operational, safety, and technical programs that would be conducted during the experimental stage of any proposed application. No effort has been expended on Project Travois for more than a year, and there is no schedule for resuming this effort because priorities for government funds have been revised in favor of other projects within the state.

In the Travois experiment, it is expected that the detonation of a 40-kt explosive placed 685 ft from the nearest free surface in terrain with a 30-deg slope would produce in excess of 7,000,000 yd^3 of quarry rock.

This is more rock than is needed to construct the Twin Springs dam, which has a crest length of 1390 ft and a maximum height of 470 ft. The haul distance from the quarry to the damsite is about 1.5 miles.

It is believed that nuclear quarries can be constructed safely within the continental United States and should be considered for all construction projects that require large volumes of broken rock. A comparison of nuclear effects between nuclear quarries and other excavation applications has been reported by Knox.[2] Data from Project Travois would provide the basis for a realistic evaluation of nuclear-quarry applications as well as contribute to a useful end product. The experiment would primarily provide the information needed to determine both the minimum radiological safety controls for this application and the most efficient techniques for recovering the quarry rock.

Information from Project Travois would also be directly applicable to the concept of using nuclear retarcs for in-situ leaching of ore deposits that are near the ground surface. Figure 14 illustrates this concept with a series of retarcs detonated simultaneously to enhance the volume of rock fractured. The solution-mining system that would be employed and the technical and practical questions that need to be resolved by experiment are similar to those discussed in the Project Sloop feasibility study.[29]

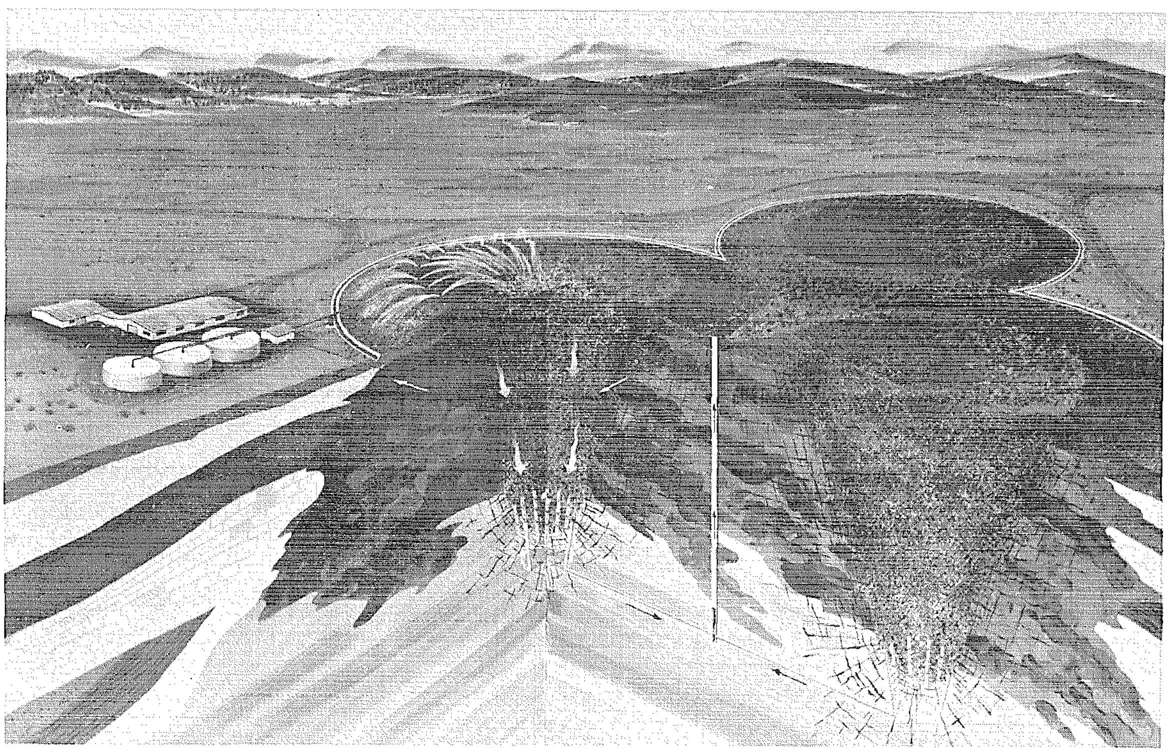

Fig. 14. Artist's concept of the use of retarcs for in-situ leaching of ore deposits.

OTHER APPLICATIONS

A number of additional concepts employing nuclear-excavation techniques have been proposed and reported, but no sense of urgency has developed to propel these concepts into a project status. Examples include the removal of overburden from ore bodies; reservoirs for flood control, irrigation, and groundwater recharge; crater-lip dams; and directed explosions for ejecta and bulk dams. In some applications, the technology has

Table V. Suggestions for possible nuclear excavations.[a]

Canals (navigation)	Water Resources (reservoirs, aqueducts)
Interoceanic Canal— Panama, Colombia	Feather River— California
Isthmus of Kra— Malaysia	Ord River— Australia
Simpson Strait— Canada	Beni River— Bolivia
Seoul (to Yellow Sea)— South Korea	Paraquay River— Argentina and Paraquay
Alternate Suez Canal— United Arab Republic	Mekong River— Southeast Asia
Luzon Island— Philippine Islands	Swamp drainage— South Korea
Parana River— Argentina	Ambuklao Reservoir (silting basin) – Philippine Islands
Madeira River— Brazil	
Mackenzie River Delta— Canada	
Canals (diversion)	Dams (landslides, construction of spillway sites, production of aggregates)
Mediterranian Sea to Chotts Depression— Tunisia, Algeria	Rio Bio-Bio (several sites)— Chile
Mediterranean Sea to Qattara Depression— United Arab Republic	Nari and Hab Rivers— Pakistan
Jonglei Canal— Sudan	Rampart Dam— Alaska
Tempisque Valley— Costa Rica	Camelback Dam— Arizona
Lake Titicaca— Bolivia	Cochiti Dam— New Mexico
Ganges to Hooghly Rivers— India	Tarbela Dam— Pakistan
Andes Mountains (east slope to west slope)— South America	Harbors
Trinity, Mad, and Eel Rivers— California	Shemya Island— Alaska
Railroad or Highway Cuts	Nome— Alaska
Boca Pass— California	Arica— Chile
Bristol Mountains— California	Salaverry— Peru
Buenaventura to Bogota— California	Cape Keraudren— Australia
Chile to Argentina (three routes)	

[a]Taken from Ref. 33.

not been sufficiently advanced to permit qualified judgments to be made on the suitability of using nuclear explosives. This is particularly true in the general area of water-resources development, where additional studies are needed to define the problem of surface- and groundwater contamination in flooded craters and retarcs.

The Soviet Union has used directed-explosion techniques for many years in the construction of earth- and rock-fill dams.[30-32] Unfortunately, these construction projects are not reported in detail. It is known that relatively small charges of chemical explosives were used in comparison with the nuclear yields that are felt to be necessary for nuclear excavation to be economically attractive. The analytical procedures used to design projects with directed chemical explosives should be applicable to nuclear explosives when the differences in the energy source are properly considered. Because of the present rate at which nuclear-excavation experiments are being performed (seven experiments since 1962), and because of the need to obtain more critical information on the effects of higher yields, material properties, and row-charge interactions, it will be many years before the techniques of directed explosions are developed to the point where large projects can be undertaken with confidence.

The greatest potential for nuclear excavation lies in underdeveloped nations. Nuclear excavation can be used to accelerate the growth and prosperity of these nations because projects not previously considered economically or technically feasible now appear to be possible. Typical projects would include the removal of natural barriers that have limited transportation or have prevented the diversion of rivers to provide the water needed for development. Water-resources projects such as dams and reservoirs would help conserve the available supply of water and prevent damage from flooding. Another possibility is a canal to connect the Qatarra Depression in the United Arab Republic with the Mediterranean Sea to provide hydroelectric power. Table V, which is a partial list of the possible nuclear-excavation applications that have been suggested, is included only to show the world-wide distribution of such projects. Many of these suggestions may not be feasible for nuclear excavation, or they may be better solved conventionally.

The impetus to proceed with such projects may come from the Non-Proliferation Treaty in which the United States and the Soviet Union have assured nonnuclear signatories of the treaty that they will not lose the potential benefits of peaceful applications if they renounce the acquisition of nuclear explosives. The United States has further announced that it will continue its research and development in the Plowshare program in order to make the benefits of such explosions available to nonnuclear signatories without delay.

CONCLUSIONS

There are useful demonstration projects that it is believed can be accomplished safely with existing technology. Examples are a deep-water harbor and a nuclear quarry. Data from such projects as these will greatly increase our knowledge of cratering and associated phenomena in a different environment from that at the Nevada Test Site. Current assessments of the feasibility of constructing a sea-level canal with nuclear explosives in Panama and Colombia are favorable from a technical viewpoint. Although additional experiments and studies will be required before this ambitious project is executed, the knowledge gained will probably eliminate some of the conservatism in the current analysis as well as provide the most economic and efficient design. The concept of close spacing in row-charge designs has made it possible to greatly reduce required salvo yields so that the seismic motions predicted for large cities near such detonations are now similar to the motions produced in populated areas by nuclear tests and earthquakes in which no real damage to residential or high-rise structures has been noted.

Nuclear excavation promises to accelerate the growth and prosperity of many nations for the benefit of all. It is an effective tool that can be developed to conserve man's most precious resource—water.

APPENDIX A: VECTOR ADDITION OF VELOCITY PROFILES

The required spacing between the explosives in a row can be estimated by adding the vertical velocity profiles of adjacent charges. The vertical mound velocities obtained in this manner should be an upper limit, for it is assumed that the peak pressures and the resulting particle velocities arrive at all points of interaction at the same time. The velocity profile used is the one that results at the ground surface primarily from spall; it does not include gas acceleration.

Figure A-1 shows the vertical velocity profile from the Sulky experiment[34] normalized to the peak velocity at surface ground zero (V_{SGZ}). Horizontal distances along the surface are shown as a fraction of the depth of burst (DOB).

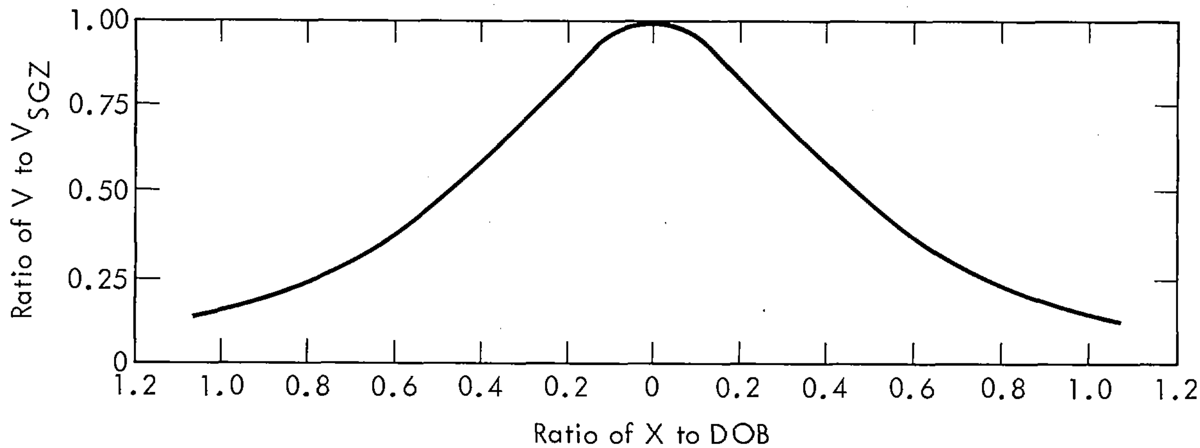

Fig. A-1. Vertical velocity profile from the Sulky experiment normalized to the peak velocity at surface ground zero (V = vertical velocity, V_{SGZ} = peak velocity at surface ground zero, X = distance along ground surface, and DOB = depth of burst).

Figure A-2 shows the resulting vector addition when the spacing (S) between explosives is 0.75DOB, or S/DOB = 0.75. The resulting average vertical velocity(V_R) along a row axis is shown to be 1.56 times the V_{SGZ} of a single charge, or V_R/V_{SGZ} = 1.56. If the DOB is chosen to be 160 ft for the 1-kt explosive, then V_R is determined to be equivalent to the peak vertical spall velocity (V_{SGZ}) of a single 2.5-kt explosive buried at 160 ft. The apparent yield (W_{ap}) of the explosives in a row is defined here as the yield of a single explosive at the same depth of burst as the row explosives that would be required to produce the peak velocity obtained by vector addition. If the row dimensions are proportional to W_{ap} as shown by points B and C'' in Fig. 1, the dimensions of the row crater will be 30% larger than that of a 1-kt cratering explosion at an optimum depth of burst.

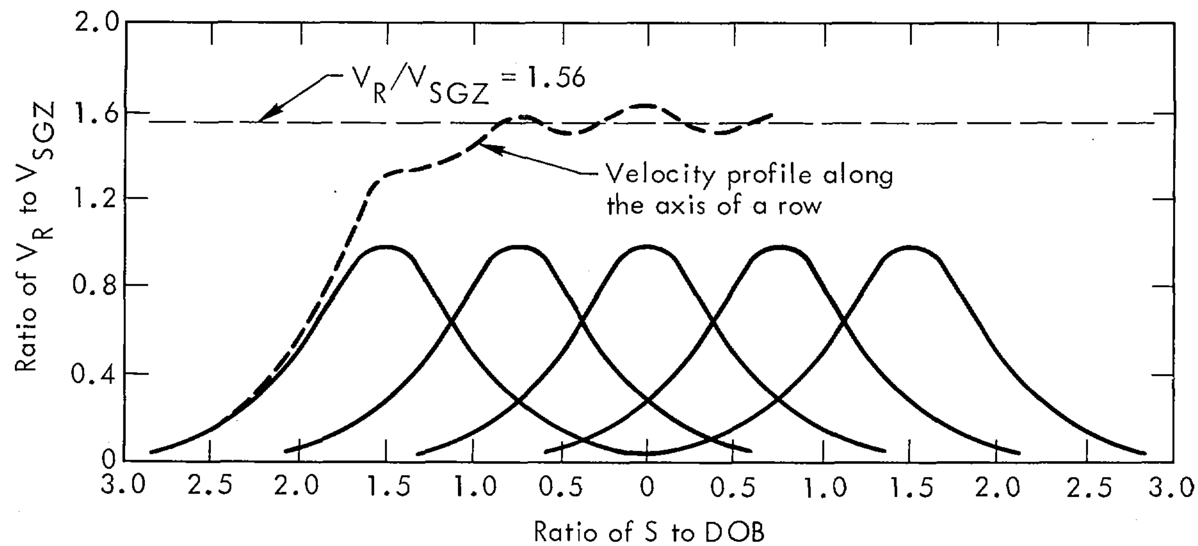

Fig. A-2. Vector addition of single-charge velocity profiles for nuclear explosions in dry, hard rock at S = 0.75DOB (V_R = average vertical velocity along row axis, V_{SGZ} = peak vertical spall velocity, S = spacing, and DOB = depth of burst).

Figure A-3 is a plot of V_R/V_{SGZ} versus S/DOB as determined from Fig. A-2. The resulting relationship for nuclear explosives in dry, hard rock is

$$V_R/V_{SGZ} = 1.2(S/DOB)^{-0.95} . \qquad \text{(A-1)}$$

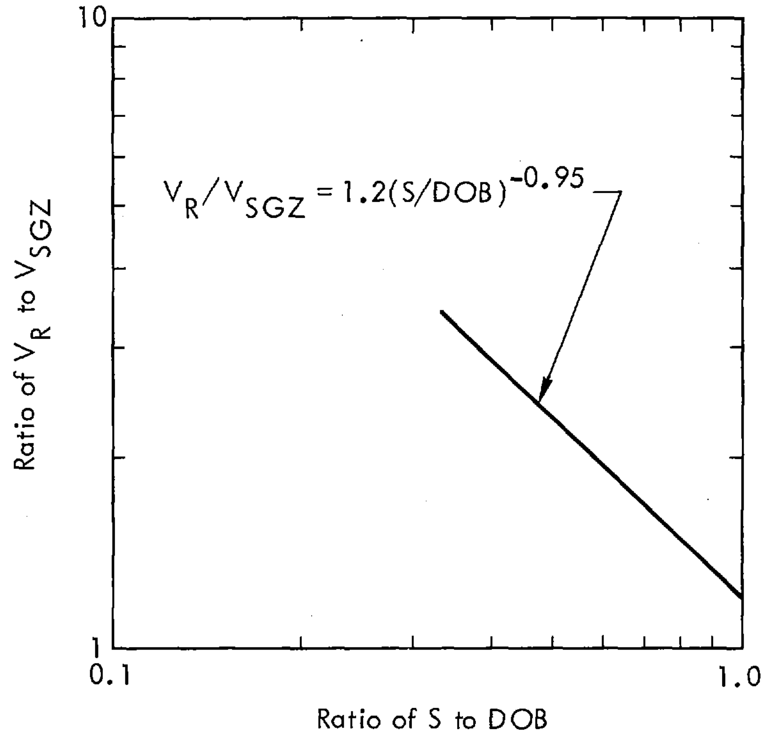

Fig. A-3. Plot of V_R/V_{SGZ} versus S/DOB for nuclear explosions in dry, hard rock (V_R = average vertical velocity along row axis, V_{SGZ} = peak vertical spall velocity, S = spacing, and DOB = depth of burst).

The next step is to determine the relationship between V_R (obtained by vector addition) and W_{ap} for dry, hard rock. This is accomplished by using the data shown in Fig. A-4, which is a plot of V_{SGZ} versus DOB for both nuclear and chemical cratering experiments. Only data from Danny Boy and Sulky are used to determine the relationship shown for nuclear explosives in Eq. A-2 because Buggy, Cabriolet, and Schooner occurred in layered rock formations having different properties.[23] For nuclear explosives, then,

$$V_{SGZ} = 2.98 \times 10^5 (DOB)^{-1.54} . \qquad \text{(A-2)}$$

From Eq. (A-2), it can be shown that

$$V_R/V_{SGZ} = \left(\frac{W_{ap}^{1/3}}{W^{1/3}}\right)^{1.54} = \left(\frac{W_{ap}}{W}\right)^{0.51} , \qquad \text{(A-3)}$$

where W is the actual yield of the row explosives. Figure A-5 is a plot of S/DOB versus W_{ap}/W as derived from Eqs. (A-1) and (A-3). The relationship is

$$S/DOB = 1.2\left[\frac{W_{ap}}{W}\right]^{-0.53} . \qquad \text{(A-4)}$$

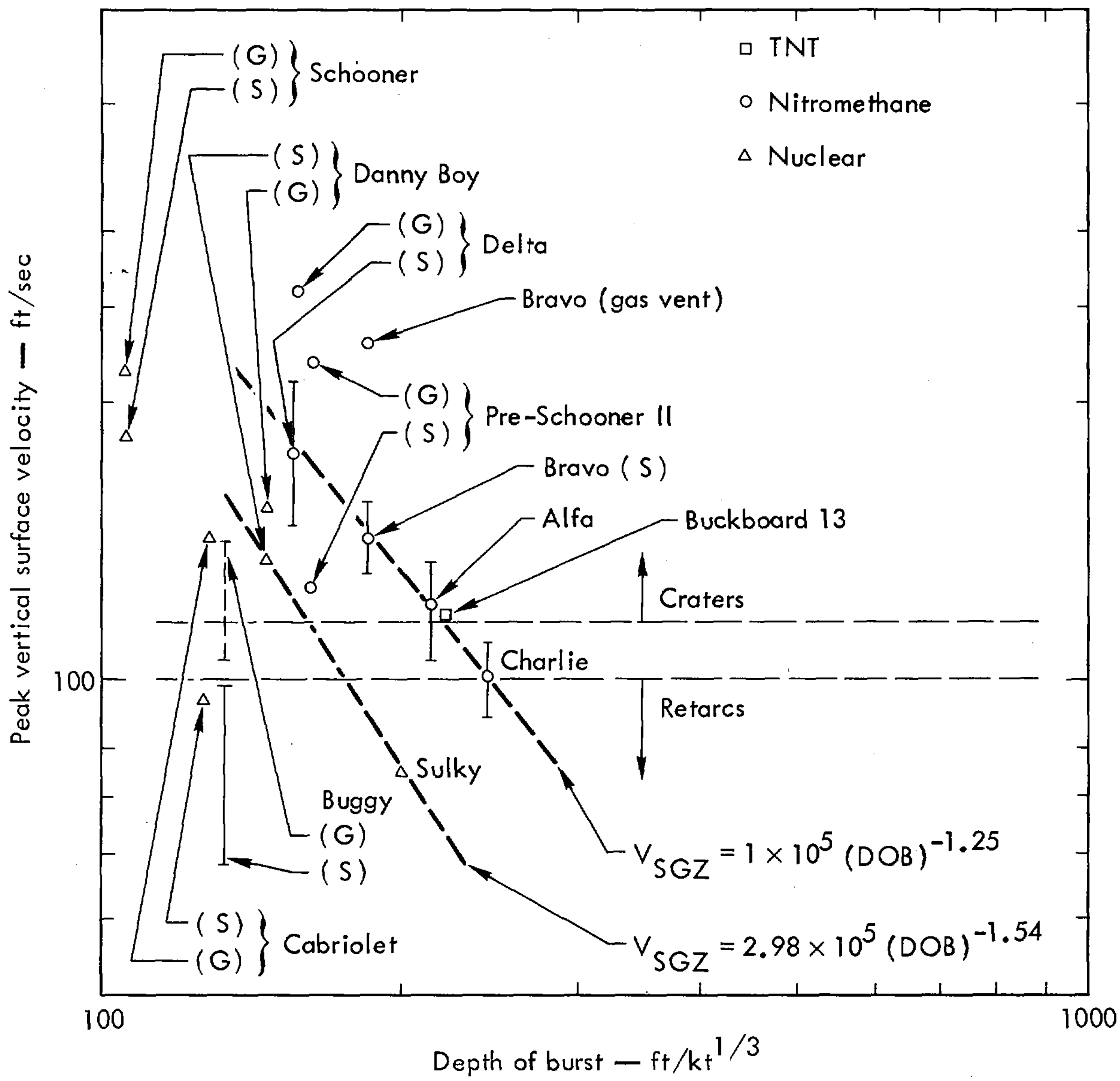

Fig. A-4. Plot of peak vertical surface velocity versus depth of burst for nuclear and chemical cratering experiments in dry, hard rock (V_{SGZ} = peak vertical spall velocity, G = acceleration due to gas, and S = acceleration due to spall).

To complete the nuclear close-spacing concept, Fig. A-6 is a plot showing the required DOB versus S/DOB for 1 kt. This was determined by selecting a peak spall velocity for the single-charge crater at the optimum point on the cratering curve. A value of 190 ft/sec was chosen for dry, hard rock. Then, for any S/DOB, a DOB is determined from Eqs. (A-1) and (A-2) such that $V_R \approx 190$ ft/sec. The resulting equations are

$$\text{DOB} = \left[\frac{3.58 \times 10^5}{V_R}\right]^{0.65} (\text{S/DOB})^{-0.62} \qquad \text{(A-5)}$$

and, for V_R = 190 ft/sec,

$$\text{DOB} \approx 135(\text{S/DOB})^{-0.62} . \qquad \text{(A-6)}$$

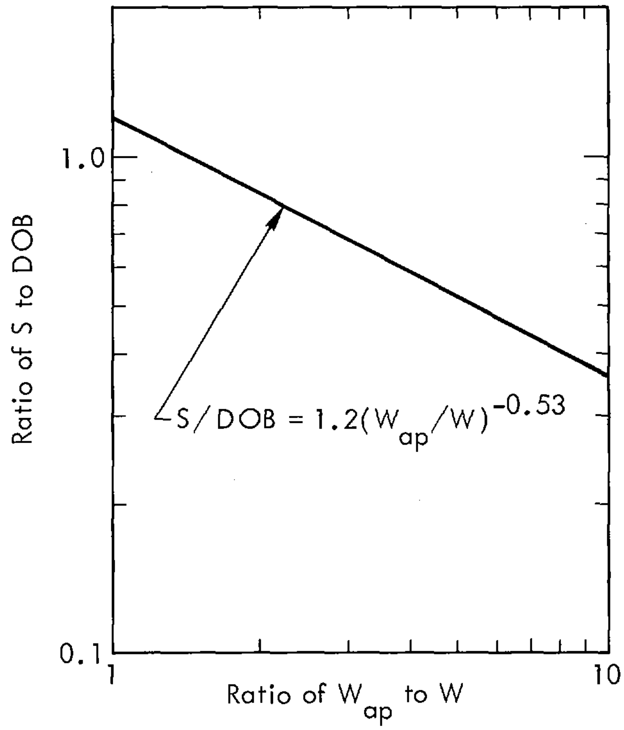

Fig. A-5. Plot of S/DOB versus W_{ap}/W for a 1-kt nuclear explosion in dry, hard rock (S = spacing, DOB = depth of burst, W_{ap} = apparent yield, and W = actual yield).

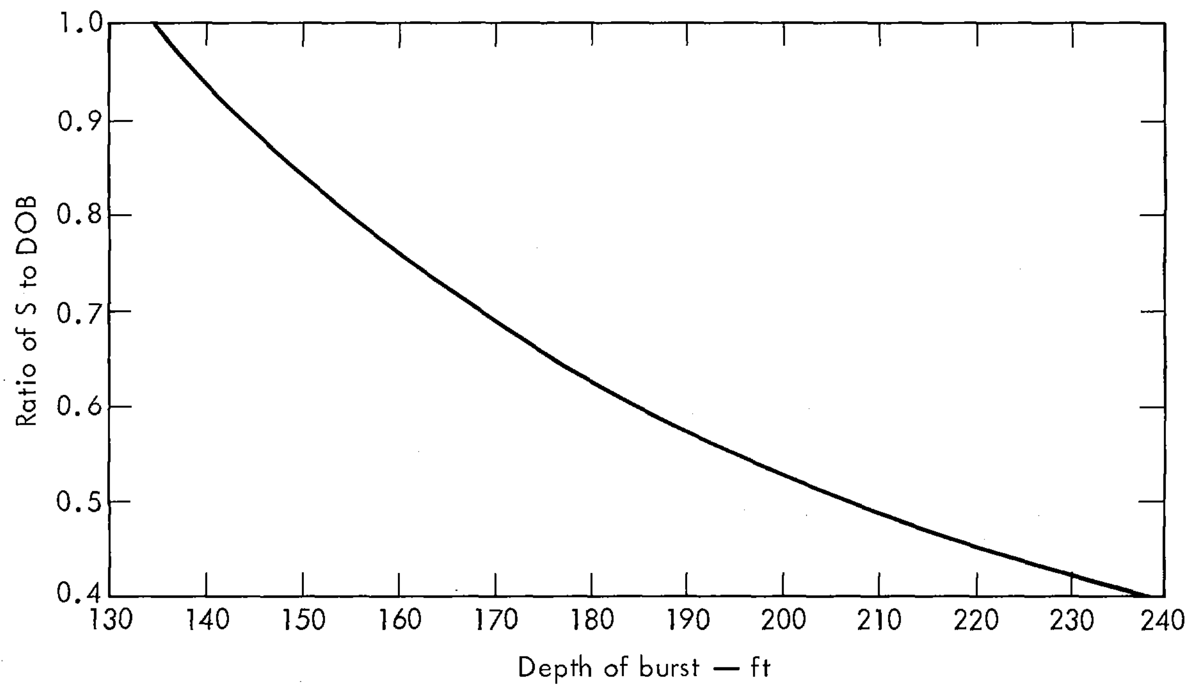

Fig. A-6. Plot of S/DOB versus DOB for a 1-kt nuclear explosion in dry, hard rock (S = spacing and DOB = depth of burst).

Finally, Fig. A-7 shows row-charge enhancement as a function of S, where S is defined as a fraction of the optimum crater radius (R_a) for 1 kt. The R_a for a 1-kt explosive in dry, hard rock is assumed to be 150 ft. For the current interoceanic-canal study, enhancements of 1.25 and 1.3 are assumed for spacings of 0.8 and 0.75R_a in comparison to the values of 1.32 and 1.45 obtained with the procedures presented here.

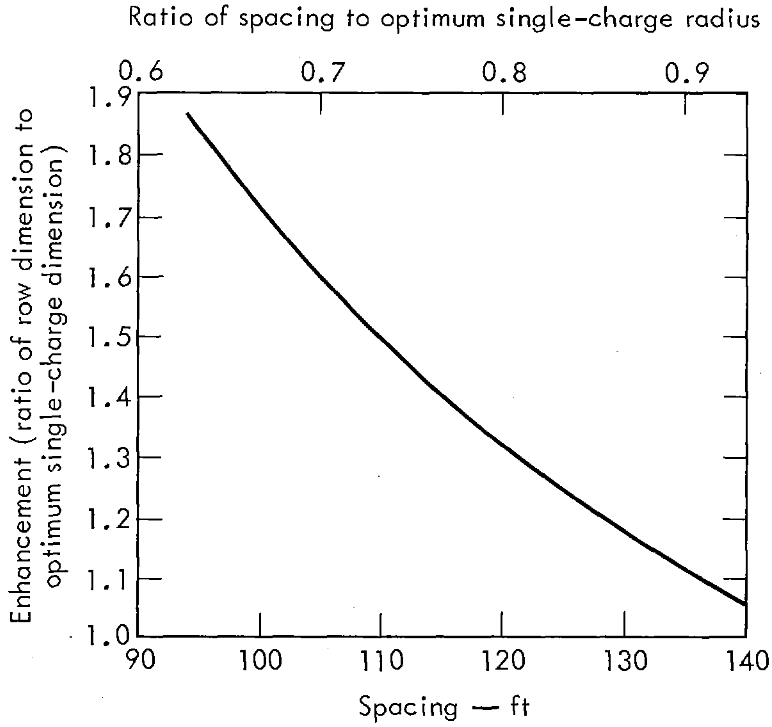

Fig. A-7. Row-crater enhancement versus spacing and S/R_a for a 1-kt nuclear explosion in dry, hard rock (S = spacing and R_a = optimum single-charge radius).

The U.S. Army Engineer Nuclear Cratering Group conducted a series of row excavations in September and October 1969 that were designed to investigate close-spacing concepts. Six rows containing from five to nine 1-ton charges of chemical explosive (nitromethane) were detonated in Bear Paw shale at Ft. Peck, Montana.[35] The preliminary results[7] are shown in Fig. A-8, in which they are compared to curves derived for chemical explosives in Bear Paw shale and nuclear explosives in dry, hard rock. The upper and lower predicted curves for shale result from the differences in the vertical surface-velocity profiles between shallow and deep charges (see next paragraph). In the nuclear case in dry, hard rock, the velocity profiles for Danny Boy and Sulky appear to be quite similar.

The upper shale curve in Fig. A-8 is based on the velocity profile of a single 1-ton charge (SC-2) that was somewhat shallower than optimum, the lower curve on that of a 1-ton charge (SC-3) much deeper than optimum.[36] The resulting relationships are

$$V_R/V_{SGZ} = 1.75(S/DOB)^{-0.89} \text{ for SC-2} \quad \text{(A-7)}$$

and

$$V_R/V_{SGZ} = 1.52(S/DOB)^{-0.89} \text{ for SC-3.} \quad \text{(A-8)}$$

The peak spall velocities versus depth of burst for chemical explosives in shale are identical to those for chemical explosives in dry, hard rock as shown in Fig. A-4. That is,

$$V_{SGZ} = 1 \times 10^5 DOB^{-1.25} . \quad \text{(A-9)}$$

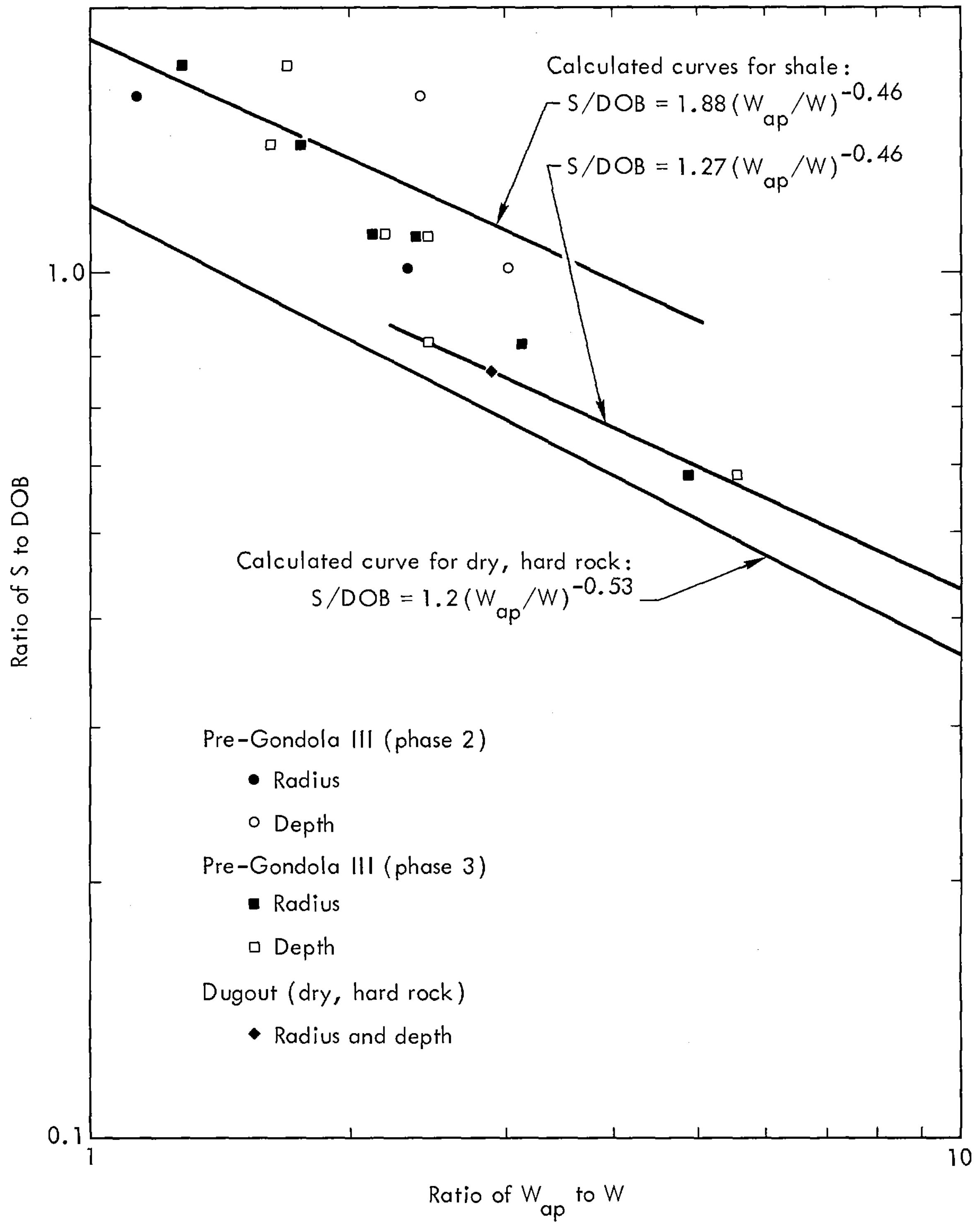

Fig. A-8. Close-spacing concept—experimental data versus calculated curves. Dugout was a nuclear experiment, the others were chemical. (S = spacing, DOB = depth of burst, W_{ap} = apparent yield, and W = actual yield).

The relationships between S/DOB and W_{ap}/W as derived from Eqs.(A-7), (A-8), and (A-9) are

$$S/DOB = 1.88\left(\frac{W_{ap}}{W}\right)^{-0.46} \quad \text{with the SC-2 profile} \qquad (A-10)$$

and

$$S/DOB = 1.27\left(\frac{W_{ap}}{W}\right)^{-0.46} \quad \text{with the SC-3 profile .} \qquad \text{(A-11)}$$

The agreement between calculated and experimental values is remarkably good in view of the number of variables and unknowns involved in row-charge experiments and the assumptions used in the vector addition of surface velocities. Only two row-charge experiments have been conducted in dry, hard rock—Dugout[37] and Buggy.[4] The spacing between the nuclear explosives in the Buggy experiment (S/DOB = 1.1) was too large for any noticeable enhancement to occur, but this cannot be stated positively because no single-charge craters exist at the Buggy site for comparison. Significant enhancement did occur in the Dugout experiment, which consisted of five 20-ton charges of nitromethane spaced 45 ft apart and buried 59 ft deep (S/DOB = 0.76). The row dimensions were 36 to 37% larger than the optimum single crater, which leads to an apparent yield of 2.8 times the actual yield. Dugout is plotted in Fig. A-8 above the nuclear curve but on the shale curve. The velocity profile applicable to Dugout is similar to that used for the lower shale curve, and the relationship of V_{SGZ} to DOB as shown in Fig. A-4 is also identical for nitromethane in both shale and dry, hard rock. A curve derived for chemical explosives in dry, hard rock would therefore be identical to the lower shale curve.

Additional field experiments are needed to further refine the close-spacing concept. Invaluable information has been gained from chemical experiments, but a nuclear row with relatively high yields is needed to provide the data necessary to refine the detonation design for a sea-level canal.

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