Aggregate Production with Nuclear Explosives

SPENST M. HANSEN and JOHN TOMAN, University of California, Lawrence Radiation Laboratory, Livermore, California

•THE DEVELOPMENT of nuclear explosives in recent years has made available a new, cheap, and powerful energy source. Project Plowshare is a research program to develop industrial and nonmilitary applications of nuclear explosive energy. The technical investigations are conducted by the University of California Lawrence Radiation Laboratory, Livermore, and sponsored by the U. S. Atomic Energy Commission.

Underground experiments in hard rock have established the rock-breaking capabilities of nuclear explosions and have provided pertinent effects data. Breaking rock for the manufacture of crushed stone aggregate is an obvious application, and one within the present technical capability of Plowshare.

EFFECTS OF UNDERGROUND NUCLEAR EXPLOSIONS IN ROCK

Figure 1 summarizes the gross effects from underground nuclear explosions at various depths of burial for a given yield. The greatest potential for aggregate production exists at depths of burst deeper than normally used for explosive excavation (Fig. 1b).

Formation, description, and phenomenology of nuclear explosion craters and cylindrical chimneys of broken rock from contained nuclear explosions are described elsewhere (see References) and will not be repeated here except as relevant to aggregate production. Experiments in rock which directly relate to aggregate production include seven chemical and seven nuclear explosions. Essential data from these are summarized in Appendices A and B.

Tonnage of Rock Broken

Results of underground and cratering explosion experiments in rock have provided tonnage data as a function of yield and depth of burst, and are the basis for the family of curves shown in Figure 2. These curves permit the prediction of broken rock tonage as a function of explosion yield and depth of burst. Specific curves are dependent on rock physical and chemical properties and will vary somewhat for different rock types.

From the shape of the curves, it is clear that for each explosion yield there is a depth of burial at which the maximum of broken rock can be produced. For hard rock the scaled depth of burst for optimum rock breaking is slightly greater than 200 $\mathrm{ft/kt}^{1/3.4}$:

$$\mathrm{Dob}' = \mathrm{Dob}/W^{1/3.4} \qquad (1)$$

where Dob′ is scaled depth of burst, Dob is depth of burst of explosive in feet, and W is yield of explosion in kilotons (kt).

Experimental Results Pertinent to Aggregate Production

1. Pre-Schooner Charlie.—The Pre-Schooner Charlie experiment, at a scaled depth of burst of 210, produced a pile of rock resembling a crater entirely above the original ground surface. The other Pre-Schooner experiments, Alfa, Bravo, and

---

Paper sponsored by Special Committee on Nuclear Principles and Applications.

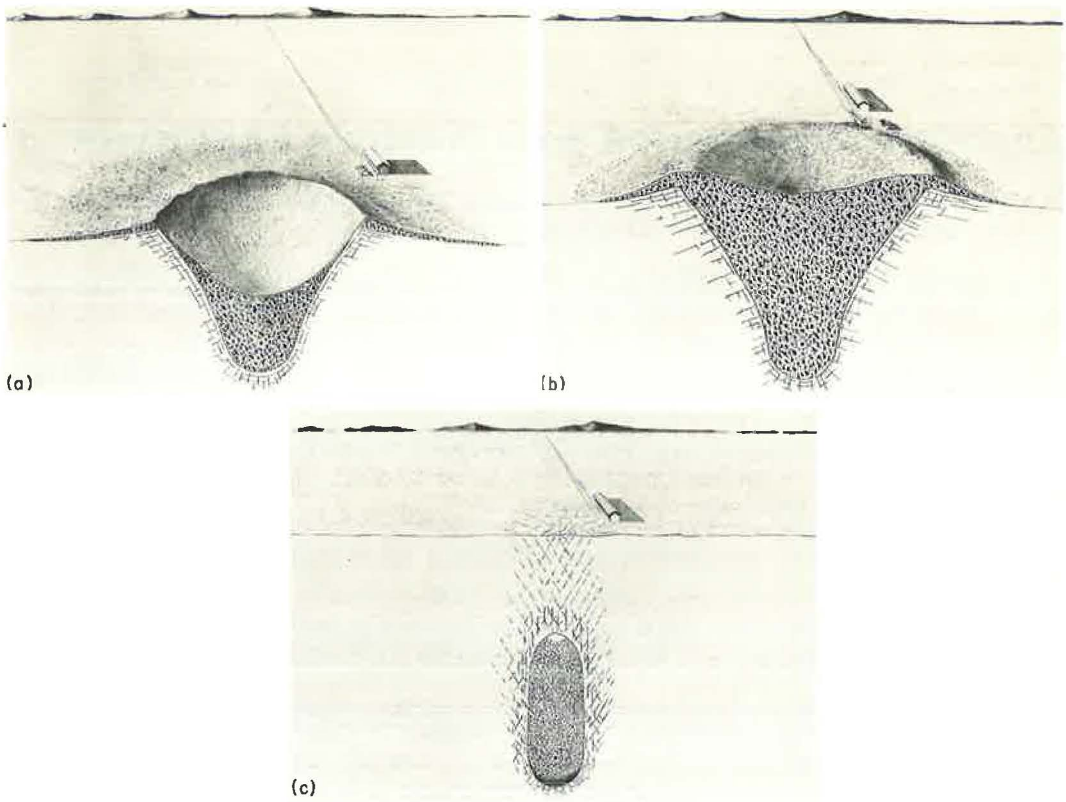

Figure 1. Effects of nuclear explosives buried at various depths: (a) optimum cratering depth $\left(\text{scaled Dob of } 140 \text{ ft/kt}^{1/3.4}\right)$; (b) maximum rock breakage depth $\left(\text{scaled Dob of } 210 \text{ ft/kt}^{1/3.4}\right)$; and (c) containment depth (scaled with 300-ft buffer overlying top of rubber column).

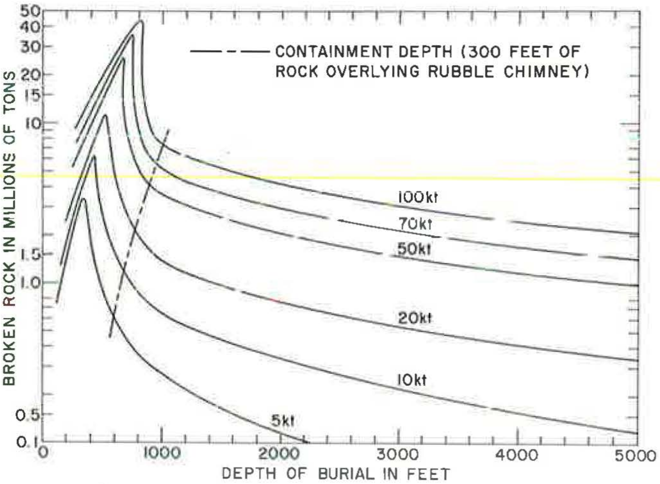

Figure 2. Tonnage curves of rock broken by underground explosions.

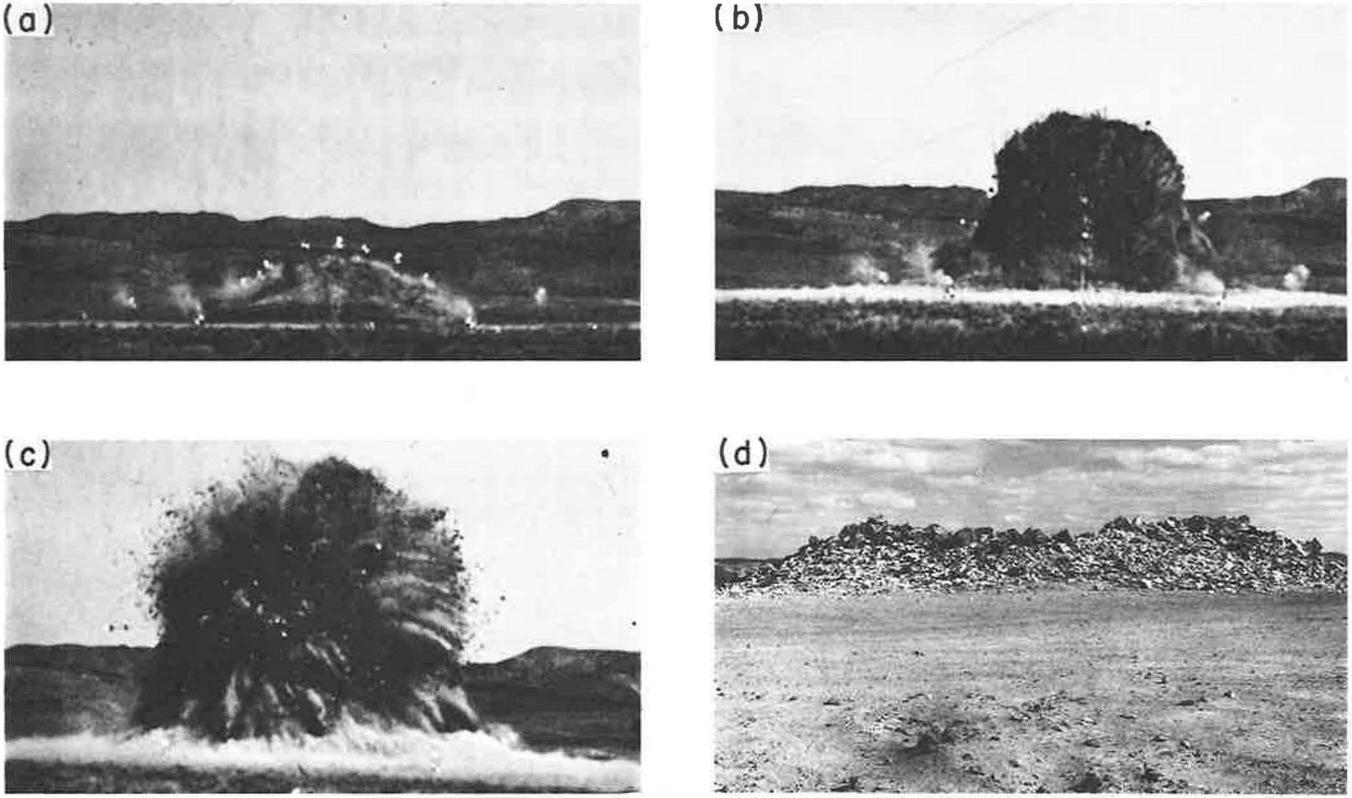

Figure 3. Pre-Schooner Charlie time-explosion sequence photographs: (a) 0.40 sec, (b) 1.20 sec, (c) 3.2 sec, and (d) postshot.

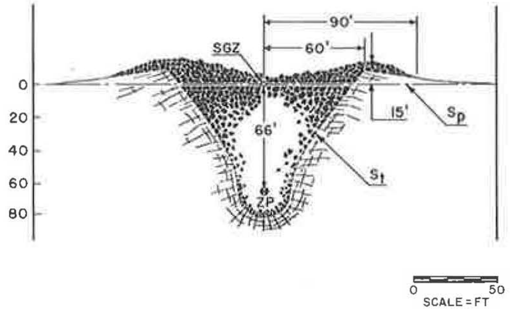

Figure 4. Schematic cross-section of Pre-Schooner Charlie crater.

Delta, which were buried at shallower depths, formed normal craters with a depression extending beneath the original ground surface. The Pre-Schooner Charlie explosion shattered the overlying rock and imparted sufficient velocity to hurl rock upward nearly vertically from the true crater (Fig. 3). The resultant rubble mound consists of fallback of explosion-broken rock. The increased volume of the rubble results from the increase in bulk of broken rock as compared to pre-explosion rock. Figure 4 is a preliminary cross-section through the Charlie experiment showing the true crater boundary and contained mass of broken rock.

Pre-explosion in-situ density was about 165 pcf. Estimates of bulk density of the rubble are about 100 pcf, giving a swell factor of approximately 1.6. Swell factor (S), used here as equivalent to the sometimes used bulking factor, is defined as the ratio of in-situ bulk density (D_i) to final bulk density of the rubble (D_r), or $S = D_i/D_r$. Swell factor may also be defined as the ratio of final postshot volume (V_f) to in-situ volume (V_i), or $S = V_f/V_i$. Estimates of bulk density and swell factor for the rubble produced by the Pre-Schooner Charlie explosion are based on data obtained by the Nuclear Cratering Group, U. S. Army Corps of Engineers, from the excavation of the Pre-Schooner Delta Crater (8) and on field observations by the authors.

2. Neptune.—The Neptune experiment was conducted at Rainer Mesa, Nevada Test Site, on a hillside with an average slope of 27 deg and at a scaled depth of burst of 189, measured normal to the average preshot slope. A cross-section of the Neptune crater is shown in Figure 5. Virtually all of the rubble ejected, plus additional slide material, was concentrated at the downhill edge of the crater and in a slide which terminated about 800 ft down the slope. No lip developed on the uphill side of the crater, but well-defined lips were formed along the sides. Neptune was fired at somewhat less than the scaled depth of burst for maximum rock breakage.

3. Danny Boy.—The Danny Boy nuclear cratering experiment (0.42 kt) conducted in basalt at the Nevada Test Site (18) yielded at least 100,000 cu yd of rock rubble and produced a crater (Fig. 6) approximately 214 ft across and 62 ft deep, measured at the preshot ground surface. The scaled depth of burst of 142 was about correct for optimum crater size. The explosion did not break as much rock as it would have with deeper burial.

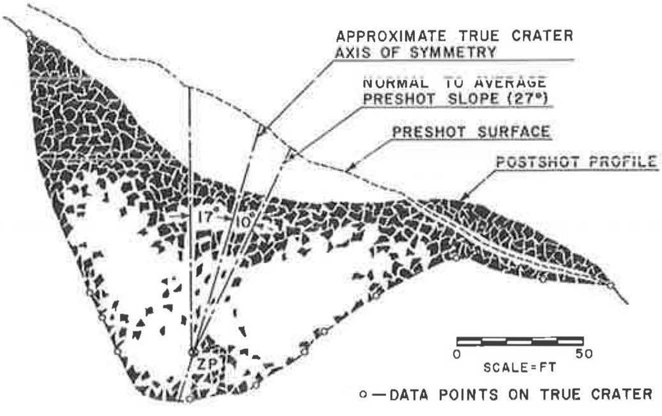

Figure 5. Schematic cross-section of Neptune crater.

Figure 6. View across Danny Boy crater showing general nature of explosion-broken rock (note man standing at upper center of photograph).

Figure 7. Rubble mound (diameter of approximately 164 ft) produced by Sulky explosion.

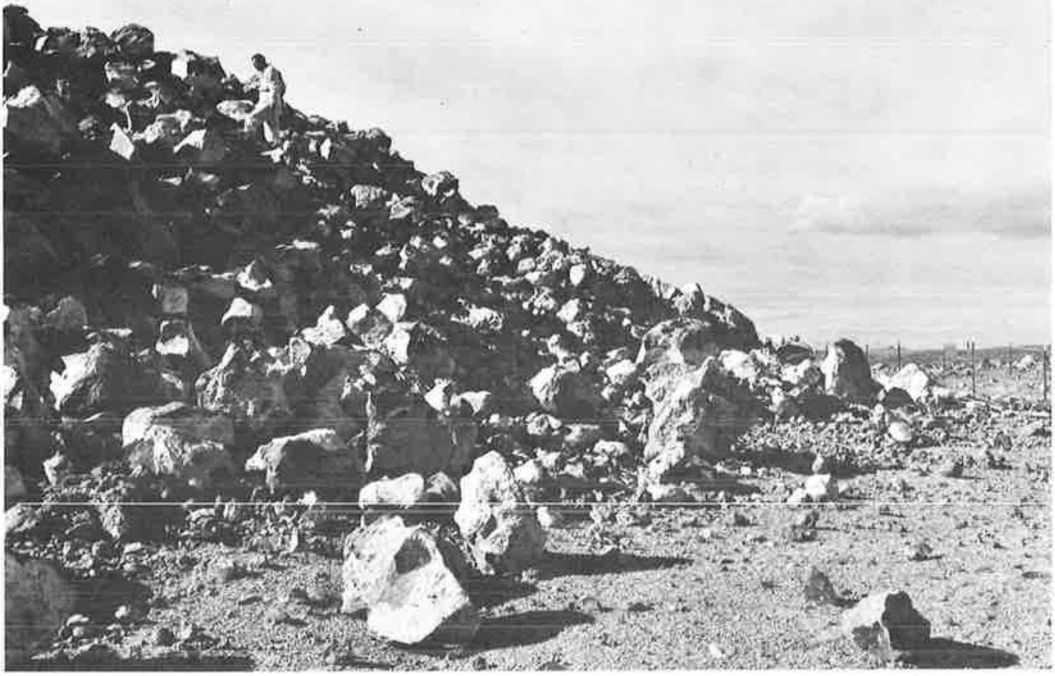

Figure 8. Edge of rubble mound formed by Sulky explosion.

Figure 9. Trench cut partially into Sulky rubble mound, showing size distribution of rock fragments; vertical bank approximately 25 ft high.

Rock size distribution data obtained by screening an 800-ton sample obtained from the crater lip indicates that the rubble produced by the explosion would be suitable for use as aggregate after sizing and/or crushing to meet standard specifications. A 200- to 400-ton/hr crusher, capable of accepting rock up to 28 by 40 in. in size, could handle at least 70 percent of all explosion-broken rock without secondary blasting. The Danny Boy experiment also provided data that established the relationship between pre-explosion joint and fracture frequency and rock fragment size.

4. Sulky.—The Sulky nuclear explosion experiment took place on Buckboard Mesa, Nevada Test Site, on Dec. 18, 1964. The explosion was detonated in hard dry basalt at a depth of about 90 ft. The approximate yield of the explosion was the equivalent of 87 tons of TNT.

A mound of rubble was formed (Figs. 7 and 8) with a maximum height of about 25 ft above the preshot ground surface and a diameter of over 160 ft. The explosive in the Sulky experiment appears to have been buried slightly too deep for maximum rock breakage, in spite of its calculated scaled depth of burst of 184. This is believed to have resulted from difficulties in scaling to very small nuclear explosive yields and from the low content of gas-forming constituents (water and carbonate) in the basalt medium. Radiation levels were sufficiently low that personnel were able to move freely about the rubble mound within a few days, and excavation of trenches and removal of broken rock began within a month. Trenches were cut by the U. S. Army Corps of Engineers with an International TD-25 bulldozer along radial lines into the mound. Figure 9 shows one of these trenches.

Fragment Size Distribution of Broken Rock

Factors that influence the overall rubble size distribution and maximum rock fragment size and shape include: (a) characteristics and frequency of natural fractures, (b) physical properties of the in-situ rock, (c) explosion yield, and (d) depth of burial. Typical fragment sizes based on data obtained by the U. S. Army Corps of Engineers from the Danny Boy and Pre-Schooner experiments in basalt on Buckboard Mesa, and on Lawrence Radiation Laboratory data from the Hardhat experiment in granite, are as follows:

Passing 6-ft sieve, 100 percent;
Passing 5-ft sieve, 95 percent;
Passing 4-ft sieve, 88 percent;
Passing 3-ft sieve, 75 percent;
Passing 2-ft sieve, 60 percent;
Passing 1-ft sieve, 40 percent;
Passing 6-in. sieve, 30 percent;
Passing 4-in. sieve, 25 percent;
Passing 2-in. sieve, 20 percent;
Passing 1- to ½-in. sieve, 16 percent;
Passing 1-in. sieve, 14 percent;
Passing ¾-in. sieve, 12 percent;
Passing ½-in. sieve, 10 percent;
Passing ⅜-in. sieve, 9 percent; and
Passing No. 4 sieve, 7 percent.

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. Fracture characteristics, such as lateral extent, amount of recementation, and spacing between break surfaces, are also significant. Fractures provide preferred sites for separation and/or breakage, and tend to limit the maximum dimensions of each rock fragment. Extensive subsurface geologic investigations of the Buckboard Mesa were conducted for the Pre-Schooner series. The U. S. Army Corps of Engineers reports that about 90 percent of the joints and natural fractures measured in vertical holes were closer than 5 ft and 50 percent were less than 1 ft (1, pp. 33-34). Explosion-broken basalt fragments on Buckboard Mesa usually show evidence of two or more sides of weathering and surface alteration, indicating these postshot fragment boundaries were preshot fracture planes. Well-developed, but unseparated, natural fractures are seldom observed transecting postshot rock fragments.

Physical properties of rock in place, including crushing strength, shear strength and tensile strength, affect overall fragmentation and the formation of new fractures. Fragment size distribution differences between broken granodiorite (strong, hard crystalline rock) in the Hardhat experiment (2) and varieties of volcanic tuff (relatively soft, low crushing strength rock) in the Rainier experiment (24, 26) illustrate the effect of physical properties on size distribution of rubble.

At depths of burst in the cratering range and near the maximum for rock breakage, shattering of rock overlying the explosion and the upward velocity imparted are dependent on both yield and depth of burial. Impact breakage of rock fragments from downward fall is also dependent on these factors.

ENGINEERING CONSIDERATIONS

Production of crushed stone from nuclear aggregate quarries will require modified methods of quarry development and rock handling. In some instances, advantages of lower cost, greater versatility and reduced development lead time will result; in others, nuclear quarrying will be less advantageous than conventional methods, or will not be applicable at all.

The emplacement and detonation of a nuclear explosive at a suitable site can produce millions of tons of broken rock more quickly than can conventional means. This broken rock can be sized and utilized directly as rough aggregate, or it can be used as raw material for the manufacture of processed aggregate. The larger sized fragments might serve to advantage as riprap or anchor rock.

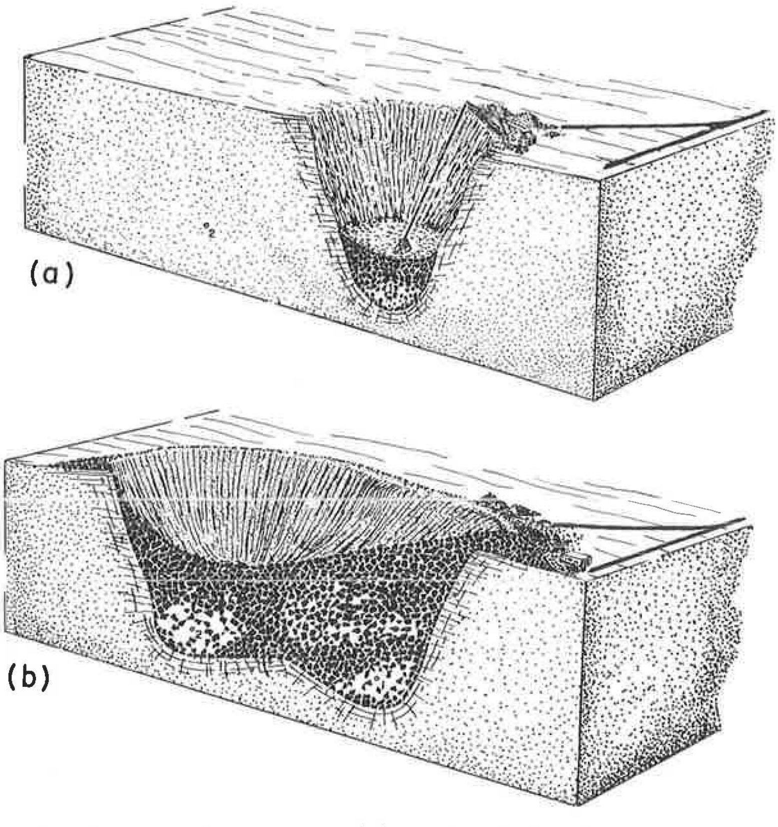

Figure 10. Multiple explosion quarry: (a) rubble mined out after first explosion, and (b) quarry after second explosion with rubble not yet mined.

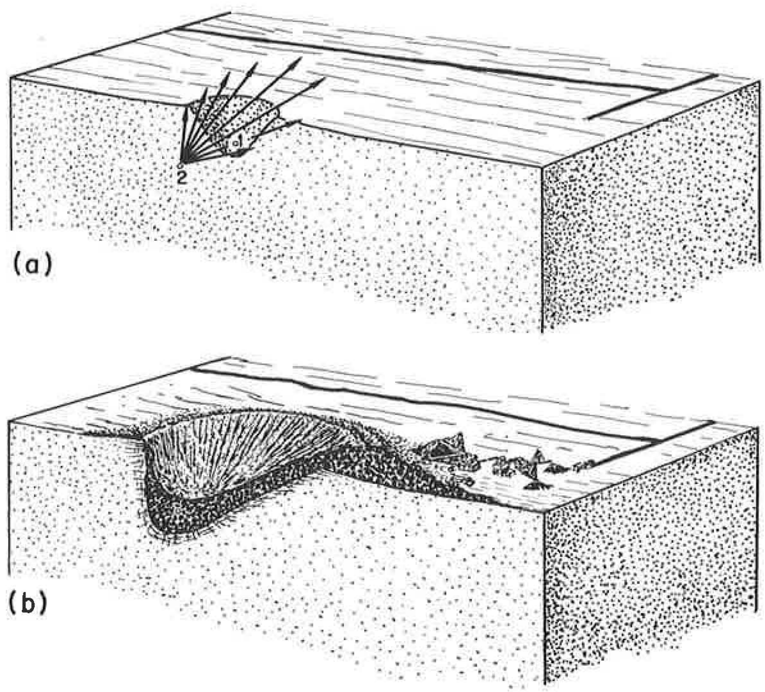

Figure 11. Aggregate quarry by directed nuclear explosion: (a) explosion placement and throwout zone; and (b) completed quarry showing location of ejected rubble.

Major engineering works, including dams, military installations, and interstate highways, are frequently located in areas remote from population centers and developed sources of aggregate. Nuclear aggregate quarrying might free such projects from construction delays caused by aggregate shortages, as well as from excessively high aggregate costs as a result of long hauls.

Site Selection

Sites suitable for the establishment of nuclear aggregate quarries will need to meet a number of requirements. Many of these are also requisite to conventional quarry development, and include: (a) the presence of rock with the desired chemical and physical properties, (b) minimum overburden or waste rock cover, (c) favorable topography, and (d) suitable natural fracture characteristics and fracture distribution. Nuclear quarry sites will also require greater thicknesses of suitable aggregate rock and will be restricted by safety problems arising from the use of nuclear explosives. The most important site limitations are expected to arise from possible seismic and shock damage to the surrounding area. Considerations of safety are briefly summarized in a later section.

Nuclear explosive quarrying techniques might make possible the use of sites where overburden or overlying rock cover prohibits the economic use of conventional explosives, and thus would relax this requirement for quarry site selection. This might be done by using nuclear explosives to strip off the overburden or by directed explosion quarrying (Fig. 7).

Quarry Layout

Several nuclear quarry designs have been considered and evaluated. Three approaches to nuclear aggregate quarry development on horizontal terrain that appear technically feasible are shown in Figures 10 and 11. The multiple explosion quarry

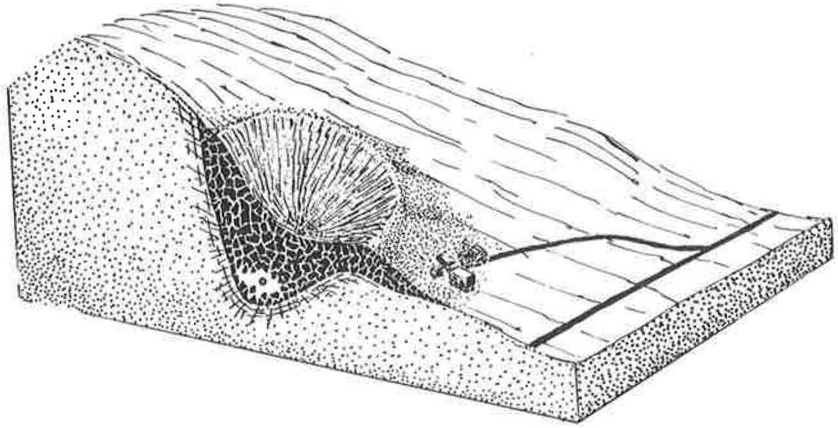

Figure 12. Aggregate quarry on a sidehill slope.

(Fig. 10b) is simply a follow-up modification of the single explosion quarry (Fig. 10a).

The directed explosion quarry is shown in Figure 11 (19). This approach utilizes a depression which could be formed by a smaller explosion buried at cratering depth, followed by a larger, more deeply buried explosion. The asymmetric placement of the larger explosion in relation to the depression causes the throwout to be directed as shown in Figure 11a. The final quarry shape, with the large mass of rubble expelled from the quarry, is shown in Figure 11b.

Explosions on a sidehill slope, buried at maximum rock-breaking depth, will produce more usable rubble for aggregate than will the same yield explosion on horizontal terrain. This is partly because gravity collapsed of the fractured zone on the uphill side of the crater adds to the total tonnage of rock broken. Also, a larger percentage of the rubble ends up outside the crater on the downhill side and rubble remaining inside the crater can be more easily removed by means of a trench cut in the downhill crater lip. The volume of rubble in the Neptune slide area alone is at least equivalent to the total volume of broken rock that would be expected from a comparable explosion at optimum cratering depth of burial on flat terrain. It is likely, therefore, that hillsides will offer preferred sites for nuclear aggregate quarries (Fig. 12).

Explosive Emplacement

Nuclear explosive packages can be emplaced by drill holes or underground drifting. At relatively shallow depths and with smaller diameter explosives, drill-hole emplacement from the surface offers cost advantages. In some instances, however, particularly when very large explosive packages are required, underground drift emplacement may be cheaper. Such a determination must be made on the basis of individual circumstances.

Standard equipment and excavation methods can likely be utilized to remove the broken rock, or new techniques might be developed. However, specific procedures can best be determined by those involved in aggregate production and marketing. A detailed discussion of this and of subsequent sizing, crushing, and other rock processing steps necessary for the production of marketable rough and processed aggregate is beyond the scope of this paper.

Because of the short time required to bring a nuclear aggregate quarry into production and the relatively small capital outlay which may be completely amortized on the basis of aggregate for a specific short-term project, long quarry life is not essential. Therefore, the aggregate source may be located close to the point of consumption, if a suitable site can be found. In such cases, considerations of long-term production and marketing will not be important factors in determining quarry location. Since aggregate is a high-bulk, low-unit value commodity, the cost of transportation becomes a major factor in the total delivered aggregate price. On a per-ton basis, using the 1964 average market price for crushed stone of $1.42 at the quarry (28), a haulage of from approximately 20 to 30 mi at $0.05 to $0.08/ton-mi doubles the quarry price.

COST OF USING NUCLEAR EXPLOSIVES TO BREAK ROCK

AEC Charges for Nuclear Explosives

During May 1964, the U. S. Atomic Energy Commission published a revised schedule of charges for nuclear explosives (9). These charges include the explosive itself and its arming and firing, but do not include safety studies, site preparation, and costs of emplacement and support. The nuclear explosive charges are $350,000 for a 10-kt yield and $600,000 for a 2-megaton yield. Interpolations for intermediate yields are based on a straight line drawn between these two charges on semilogarithmic paper and are to be considered only approximations (Fig. 13).

The cost of energy on a per-unit basis from nuclear explosives is substantially lower than that from conventional explosives. The comparison is summarized in Table 1.

TABLE 1

APPROXIMATE COST OF EXPLOSIVE ENERGY

Explosive	$1 Million BTU's
TNT	115.00
Dynamite	100.00
Ammonium nitrate-fuel oil	30.00
Nuclear:	
10-kt	8.75
100-kt	1.12
1-megaton	0.145
2-megaton	0.075

Nuclear explosives can be designed to optimize particular characteristics such as explosive package size, cost, and radioactive by-products. Trade-offs between desirable properties often must be made in the selection of a nuclear explosive device for a project. Of particular interest for applications in aggregate production, as in many industrial applications, is the explosive package size. The minimum explosive sizes published by the Atomic Energy Commission are 10-kt yield with a cylindrical canister 12 in. in diameter for emplacement in a 13-in. I.D. drill hole and 100-kt yield with a cylindrical canister 18 in. in diameter for emplacement in a 19-in. I.D. drill hole. These minimum sizes do not necessarily

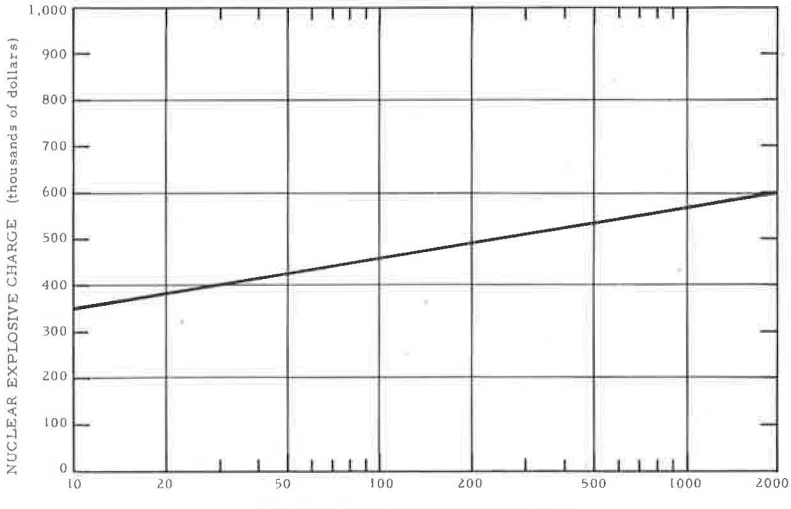

Figure 13. Projected charges for thermonuclear explosives.

TABLE 2

COST ESTIMATES FOR BREAKING ROCK WITH NUCLEAR EXPLOSIVES

Explosion Yield (kt)	Approx. Explosion Charge ($)	Million Tons of Rock Broken	Approx. Emplacement and Other Costs[a]	Total Costs ($)	Cost of Rock Broken ($/ton)
10	350,000	6 million	200,000	550,000	0.092
20	390,000	11 million	225,000	615,000	0.056
50	425,000	25 million	250,000	675,000	0.027
70	450,000	33 million	275,000	725,000	0.022
100	475,000	43 million	300,000	775,000	0.018

[a] Safety costs not included; must be evaluated separately for each individual site, and may be prohibitively high in some instances.

correspond to the nuclear explosive charge data summarized in Table 1, since charges for explosives with special characteristics, including minimum size, can be expected to be somewhat higher.

Per-Ton Costs of Breaking Rock with Nuclear Explosives

Cost estimates given in Table 2 are believed to be reasonable approximations for breaking rock with nuclear explosives for aggregate quarrying on a repeating, production-line basis. Included in these cost estimates are AEC charges for nuclear explosives and their arming and firing, emplacement and related engineering costs for site development, and support and other miscellaneous costs. Not included are the direct costs of safety studies and expenditures for the indemnification of any resultant postshot damage. Expenses resulting from considerations of safety vary greatly and are highly dependent on the specific project, the region in which it is carried out, and whether or not it is a single explosion or one of a series.

As may be noted, the per-ton cost of rock breakage with nuclear explosives is comparable to or lower than with conventional techniques. The advantage increases with the use of larger yield explosives. The cost estimates are only of breaking rock and do not include major items such as site acquisition, extracting rubble from the quarry, or any subsequent treatment necessary including crushing, sizing, screening, and washing.

SAFETY CONSIDERATIONS

Any use of nuclear explosives will require careful attention to problems of safety. To date, the Atomic Energy Commission and the Lawrence Radiation Laboratory have gained experience from the detonation of more than 100 nuclear explosives underground at the Nevada Test Site and elsewhere. Data gathered from these tests and from follow-up investigations have provided a basis for reliable preshot assessments of potential hazards from shock and radioactivity. Techniques have been developed for avoiding or minimizing most of these.

Shock and Seismic Effects

Experience from underground explosions, together with a theoretical understanding of pertinent phenomena, permits the reasonably accurate prediction of shock magnitude as a function of distance from the explosion. Table 3 gives a summary of damage categories based on peak surface velocity, a quantity found to be the most effective measure of shock damage (4). These data permit an estimate of the damage threshold distances for equipment and structures in the vicinity of a given shot. Variations in the wave form, seismic path, and particular structures add significant uncertainty to

TABLE 3

STRUCTURAL DAMAGE THRESHOLDS FOR BUILDINGS AND EQUIPMENT NEAR UNDERGROUND NUCLEAR EXPLOSIONS

Type of Structure	Type of Damage	Peak Surface Velocity Threshold, Major Damage (cm/sec)	Corresponding Scaled Distance in Granite[a] ($ft/kt^{1/3}$)
Residential (old)	Plaster cracking	10	2, 500
Residential, concrete block	Cracking	20	1, 250
Cased drill holes	Vertical displacement, horizontal offset	40-50	750-550
Mechanical equipment (pumps, compressors, generators, etc.)	Skids bent, shafts misaligned	100	375
Prefab metal buildings on concrete pads	Cracked pads, distorted steel	150	250
Rigid steel tanks, 50 gal to several thousand gallons	Buckling	≥300	125
Utility poles	Falling	≥300	125

[a] Distances are for structures resting directly on a hard crystalline rock such as granite, with the explosion detonated in the same medium, and do not include a safety factor. They are, therefore, a minimum and apply only to this ideal case. For most industrial applications, distances would probably be substantially increased (doubled or more) to provide a safety factor and to take into account possible presence of different and less favorable geologic conditions.

the values listed in Table 3. Prediction of damage will require the detailed evaluation of specific sites. Protection of personnel and portable equipment can be assured by moving them a safe distance from the detonation. Damage to stationary equipment and structures can be estimated before the shot, and the cost of the expected damage can be written off as a production cost.

Air blast is a major consideration for nuclear explosives at very shallow depths of burial or in the atmosphere. However, for shots buried at maximum rock-breakage depths, the zone of air blast damage can be expected to lie well inside the region of expected seismic damage.

Radioactivity

All nuclear explosives have some radioactive by-products. The amounts and types of activity are dependent on the energy yield and type of explosive. At the scaled depths of burst utilized for aggregate production, the venting to the atmosphere would carry only about 0.1 percent of the total fission radioactivity produced and would be a manageable hazard. Based on experience from the Danny Boy and Sulky experiments, a small amount of highly vesiculated rock melt with low specific radioactivity would be distributed throughout the rubble. The small amount of this material and its low level of radioactivity is not expected to be a hazard to personnel or to restrict in any way the utilization of the rock broken by the explosion.

In some instances it may be necessary for operating personnel to wear respirators or to take other standard precautions. However, the continued development of relatively clean nuclear explosives will tend to reduce even further the radioactivity safety problems encountered in the open-pit mining of aggregate.

The possibility of groundwater contamination by radioactive fission products has been extensively investigated. The radioactive materials trapped in solidified rock melt at the base of the original explosion cavity and distributed throughout the rubble will probably not cause serious groundwater contamination problems (23).

CONCLUSIONS

Breaking rock with nuclear explosives for use as rough aggregate or as raw material for the manufacture of processed aggregate is now technically feasible, as has been demonstrated by underground experiments in hard rock. Limitations arising from safety considerations are not excessive and will permit the use of nuclear explosives at many sites.

The greatest spur to the introduction of nuclear explosives as a tool for breaking rock in the multibillion-dollar aggregate-using industries will be the great potential for increasing the availability of high-quality crushed stone aggregate and doing so cheaply. Under favorable circumstances, the total per-unit cost of crushed stone from a nuclear explosion quarry, after sizing and all necessary processing, can be lower than the cost of a similar product produced by conventional methods.

Technical questions still remain to be answered in such areas as the use of multiple nuclear explosives and methods of removing broken rock from the nuclear explosion quarry. These will be solved in due course as commercial applications develop and industrial experience with nuclear aggregate quarrying is obtained.

REFERENCES

1. Banks, D. C., and Saucier, R. T. Geology of Buckboard Mesa. U. S. Army Engineer Waterways Exp. Sta., Vicksburg, Miss., PNE-5001, 1964. 147 pp.
2. Boardman, C. R., Rabb, D. D., and McArthur, R. D. Characteristic Effects of Contained Nuclear Explosions for Evaluation of Mining Applications. Lawrence Radiation Lab., UCRL-7350, 1963. 106 pp.
3. Butkovich, T. R., Calculation of the Shock Wave From an Underground Nuclear Explosion. In Engineering with Nuclear Explosives, pp. 35-50. Proc. 3rd Plowshare Symposium, U. S. AEC, Div. of Tech. Info., TID-7695, 1964.
4. Cauthen, L. J. Effects of Seismic Waves on Structures and Other Facilities. Lawrence Radiation Lab., UCRL-7773, 1964. 36 pp.
5. Circeo, L. J. Engineering Properties and Applications of Nuclear Excavations. Lawrence Radiation Lab., UCRL-7657, 1964. 46 pp.
6. Curry, R. L. Investigation of the Feasibility of Manufacturing Aggregate by Nuclear Methods. U. S. Army Engineer Waterways Exp. Sta., Misc. Paper No. 6-643, 1964. 19 pp.
7. Fisher, P. R. Large Diameter Drilling for Emplacing Nuclear Explosives. In Engineering with Nuclear Explosives, pp. 239-268. Proc. 3rd Plowshare Symposium, U. S. AEC, Div. of Tech. Info., TID-7695, 1964. pp. 239-268.
8. Frandsen, A. D. Pre-Schooner Postshot Exploration. U. S. Army Engineer Nuclear Cratering Group, Memo. 64-779, 1964.
9. Frank, W. J. The Characteristics of Nuclear Explosives. Lawrence Radiation Lab., UCRL-7870, 1964. 5 pp.
10. Hansen, S. M., and Lombard, D. B. Completely Contained Nuclear Explosives for Mining by Caving. In Engineering with Nuclear Explosives, pp. 371-384. Proc. 3rd Plowshare Symposium, U. S. AEC, Div. of Tech. Info., TID-7695, 1964.
11. Hansen, S. M., et al. Recommended Explosion-Crater Nomenclature. Geophysics, Vol. 29, No. 5, pp. 772-773, 1964.
12. Higgins, G. H. Evaluation of the Ground Water Contamination Hazard from Underground Nuclear Explosions. Jour. Geophysical Res., Vol. 16, No. 10, pp. 1509-1519, 1959.

13. Johnson, G. W., and Violet, C. E. Phenomenology of Contained Nuclear Explosions. Lawrence Radiation Lab., UCRL-5124, Rev. 1, 1958. 27 pp.
14. Johnson, G. W., Higgins, G. H., and Violet, C. E. Underground Nuclear Detonations. Lawrence Radiation Lab., UCRL-5626, 1959. 44 pp.
15. Leisek, J. F. Post-Shot Geologic Investigations of the Danny Boy Nuclear Cratering Experiment in Basalt. Lawrence Radiation Lab., UCRL-7803, 1964. 29 pp.
16. Nordyke, M. D. On Cratering—A Brief History, Analysis and Theory of Cratering. Lawrence Radiation Lab., UCRL-6578, 1961. 72 pp.
17. Nordyke, M. D., Nuclear Excavation Technology. Lawrence Radiation Lab., UCRL-7658, 1964. 23 pp.
18. Nordyke, M. D., and Wray, W. R. Preliminary Summary Report, Project Danny Boy. Lawrence Radiation Lab., UCRL-6999, 1962. 39 pp.
19. Pokrovskii, G. I., Fedorov, I. S., and Dokuchaev, M. M. Theory and Practice of Dam Construction by Directed Explosions. Transl. Lawrence Radiation Lab., UCRL-Trans-1035(L), 1951. 154 pp.
20. Rabb, D. D. Block Caving, Nuclear Style. Mining Eng., Vol. 16, No. 3, pp. 48-52, 1964.
21. Shelton, A. V., Nordyke, M. D., and Goeckermann, R. H. The Neptune Event—A Nuclear Explosive Cratering Experiment. Lawrence Radiation Lab., UCRL-5766, 1960. 32 pp.
22. Skrove, J. W., and McArthur, R. D. Post-Shot Geologic Studies of the Excavations in Neptune Crater. Lawrence Radiation Lab., UCRL-6812-T, 1962. 28 pp.
23. Stead, F. W. Distribution in Groundwater of Radionuclides from Underground Nuclear Explosions. In Engineering with Nuclear Explosives. pp. 127-138. Proc. 3rd Plowshare Symposium, U. S. AEC, Div. of Tech. Info., TID-7695, 1964.
24. Thompson, T. L., and Misz, J. B. Geologic Studies of Underground Nuclear Explosions Rainier and Neptune—Final Report. Lawrence Radiation Lab., UCRL-5757, 1959. 58 pp.
25. Todd, D. K. Economics of Ground Water Recharge by Nuclear and Conventional Means. Lawrence Radiation Lab., UCRL-7850, 1964. 135 pp.
26. Warner, S. E., and Violet, C. E. Properties of the Environment of Underground Nuclear Detonations at the Nevada Test Site, Rainier Event. Lawrence Radiation Lab., UCRL-5542, 1959. 21 pp.
27. Zodtner, H. H. Operations and Safety Problems Associated with a Nuclear Excavation Project. Lawrence Radiation Lab., UCRL-7656, 1964. 18 pp.
28. Crushed Stone. Rock Mining and Processing, Vol. 68, No. 1, pp. 60-61, Jan. 1965.

Appendix A

NUCLEAR CRATERING EXPERIMENTS IN ROCK

(Listed in Order of Increasing Scaled Depth of Burst)

Cratering Depth (Scaled Depth of Burst Less Than 200)

Buckboard No. 11—Explosive type, TNT; yield, 20 tons; scaled depth of burst, 81; depth of burial, 25.5 ft; rock type, basalt; apparent crater radius, 44.7 ft; apparent crater depth, 24.9 ft; firing date, Sept. 14, 1960; location, Buckboard Mesa, NTS.

Pre-Schooner Delta—Explosive type, nitromethane; yield, 20 tons; scaled depth of burst, 132.5; depth of burial, 41.8 ft; rock type, basalt; apparent crater radius, 46.1 ft; apparent crater depth, 25.6 ft; firing date, Feb. 27, 1964; location, Buckboard Mesa, NTS.

Buckboard No. 12—Explosive type, TNT; yield, 20 tons; scaled depth of burst, 135; depth of burial, 42.7 ft; rock type, basalt; apparent crater radius, 57.0 ft; apparent crater depth, 34.7 ft; firing date, Sept. 27, 1960; location, Buckboard Mesa, NTS.

Danny Boy—Explosive type, nuclear; yield, 0.42 ± 0.08 kt (1 kt equivalent to the explosive release of 10^{12} calories of energy and approximately equal to the energy released by the detonation of 1,000 tons of TNT); scaled depth of burst, 142; depth of burial, 110 ft; rock type, basalt; apparent crater radius, 107 ft; apparent crater depth, 62 ft; firing date, March 5, 1962; location, Buckboard Mesa, NTS.

Pre-Schooner Bravo—Explosive type, nitromethane; yield, 20 tons; scaled depth of burst, 159; depth of burial, 50.2 ft; rock type, basalt; apparent crater radius, 49.0 ft; apparent crater depth, 25.5 ft; firing date, Feb. 13, 1964; location, Buckboard Mesa, NTS.

Pre-Schooner Alfa—Explosive type, nitromethane; yield, 20 tons; scaled depth of burst, 184; depth of burial, 58.0 ft; rock type, basalt; apparent crater radius, 50.3 ft; apparent crater depth, 22.9 ft; firing date, Feb. 6, 1964; location, Buckboard Mesa, NTS.

Sulky—Explosive type, nuclear; yield, 87 ± 4 tons; scaled depth of burst, 184; depth of burial, 90 ft; rock type, basalt; average rubble mound radius, 79 ft; average rubble mound height, 21 ft; firing date, Dec. 18, 1964; location, Buckboard Mesa, NTS.

Buckboard No. 13—Explosive type, TNT; yield, 20 tons; scaled depth of burst, 186; depth of burial, 58.8 ft; rock type, basalt; apparent crater radius, 36.8 ft; apparent crater depth, 16.2 ft; firing date, Aug. 24, 1960; location, Buckboard Mesa, NTS.

Neptune—Explosive type, nuclear; yield, 115 ± 15 tons; scaled depth of burst, 189 (normal distance to nearest surface); vertical depth of burial, 109.5 ft; shortest distance to surface, 98.5 ft; rock type, welded tuff; apparent crater radius, 100 ft; apparent crater depth, 35 ft; firing date, Oct. 14, 1958; location, Rainier Mesa, NTS.

Intermediate Depth (Scaled Depth of Burst Between 200 and Containment)

Pre-Schooner Charlie—Explosive type, nitromethane; yield, 20 tons; scaled depth of burst, 210; depth of burial, 66.1 ft; rock type, basalt; rubble mound radius, 130 ft; average rubble mound height, 15.9 ft; firing date, Feb. 25, 1964; location, Buckboard Mesa, NTS.

Blanca—Explosion type, nuclear; yield, 19.0 ± 1.5 kt; scaled depth of burst, 312; vertical depth of burial, 988 ft; shortest distance to surface, 835 ft; rock type, welded tuff; depth of collapse crater at surface, 25 ft; approximate tonnage of rock broken, 22 million tons; firing date, Oct. 30, 1958; location, Rainier Mesa, NTS.

Containment[1] Depth (Buffer of Rock 300 Ft Thick Overlying Collapse Chimney)

Shoal—Explosion type, nuclear; yield, 12.5 kt; scaled depth of burst (for containment explosions measured in units of feet/$W^{1/3}$ rather than feet/$W^{1/3.4}$ used for cratering and intermediate depth explosions), 520; depth of burial, 1,205 ft; rock type, granite; cavity radius, 84 ft; chimney height, 356 ft; approximate tonnage of rock broken, 750,000 tons; location, Churchill County, Nevada.

Hardhat—Explosion type, nuclear; yield, 5.0 kt; scaled depth of burst, 550; depth of burial, 939 ft; rock type, granodiorite; cavity radius, 63 ft; chimney height, 281 ft; approximate tonnage of rock broken, 250,000 tons; location, Climax Stock, NTS.

Rainier—Explosion type, nuclear; yield, 1.7 kt; scaled depth of burst, 663; depth of burial, 899 ft; rock type, welded tuff; cavity radius, 65 ft; chimney height, 386 ft; approximate tonnage of rock broken, 500,000 tons; location, Rainier Mesa, NTS.

---

[1] Containment is used here to mean that gross explosion effects, such as surface subsidence, the ejection of rock fragments, and rubble mound formation, are prevented from developing at the surface by rock overlying the explosion. Contained, therefore, does not necessarily mean that radioactive by-products from the explosion do not reach the surface by seepage through fractures or other means. In other words, the explosion but not necessarily all of the radioactivity, is contained. Containment can usually be achieved by a buffer zone from 300 to 500 ft thick, depending on rock characteristics, overlying the gravity collapse rubble chimney.

Appendix B

SUMMARY OF HARD ROCK CRATERING DATA

Event[a]	Yield[b] (tons)	Explosive[c]	Dob (ft)	Dob'[d] $\left(ft/kt^{1/3.4}\right)$	R_a (ft)	R_a'[d] $\left(ft/kt^{1/3.4}\right)$	D_a (ft)	D_a'[d] $\left(ft/kt^{1/3.4}\right)$	Scaled Volumes[e] (10^4 cu yd/$kt^{0.88}$)				
									V_{br}'[f]	V_t'[g]	V_a'	V_{fb}'[i]	V_e'[j]
Buckboard No. 11	20	TNT	25.5	81	44.7	142	24.9	79	7.83	8.9	6.2	2.7	8.25
Pre-Schooner Delta	20	CH_3NO_2	41.8	132	46.1	146	25.6	81	14.0	15.7	7.46	8.24	14.86
Buckboard No. 12	20	TNT	42.7	135	57.0	180	34.7	110	21.33	22.4	15.5	6.9	23.0
Danny Boy	420	Nuclear	110	142	107	139	62	80	14.5	16.1	7.28	8.82	12.18
Pre-Schooner Bravo	20	CH_3NO_2	50.2	159	49.0	155	25.5	81	19.43	20.5	8.75	11.75	15.45
Pre-Schooner Alfa	20	CH_3NO_2	58.0	183	50.3	159	22.9	73	23.53	24.6	8.74	15.86	17.14
Buckboard No. 13	20	TNT	58.8	186	36.8	117	16.2	51	14.03	15.1	2.66	12.44	7.16
Neptune	115	Nuclear	98.5	189	100	189	35.0	66	29	30	14.7	15.3	22.8[k]
Pre-Schooner Charlie	20	CH_3NO_2	66.1	210	R-57[l]	180	—	—	36.9	38.0	—	51.8	—

[a] With exception of Neptune, all events tabulated were fired in basalt on Buckboard Mesa at AEC Nevada Test Site.

[b] Yields of high explosives shown are actual charge weights with 1 ton = 2,000 lb of explosive; Nuclear yields are defined as 1 ton = 10^9 calories.

[c] Twenty-ton TNT charges are formed from 36-lb blocks of cast TNT (density of 1.53 gm/cu cm) stacked to approximate spherical charge. Nitromethane (CH_3NO_2) is liquid used primarily as solvent; under conditions of confinement, it can be made to detonate with properties similar to TNT. The 20-ton charges were contained in leak-tight spherical cavities.

[d] Dob', R_a', D_a' are scaled depth of burst, apparent crater radius, and apparent crater depth, respectively; yield in kilotons to $1/3.4$ power is scaling factor; scaled dimensions shown would be real dimensions for yield of 1 kt.

[e] Scaling of volumes as 0.88 power of yield for cratering shots is natural consequence of cubing dimensions which are scaled to $1/3.4$ power of explosive yield; i.e., $\left(kt^{1/3.4}\right)^3 = kt^{0.88}$. Volumes for completely contained shots are directly proportional to yield since chimney height is linear function of cavity radius which scales as yield to $1/3$ power.

[f] V_{br}' is total scaled volume of in-situ rock broken and available for aggregate. It is calculated as volume of true crater, V_t', minus volume of initial spherical cavity formed on detonation. Computed V_{br}' is conservative since much broken rock in rupture zone outside true crater surface which is also available for aggregate is not included. An in-situ density of 2.6 gm/cu cm was used to determine tonnage from V_{br} column for Figure 2.

[g] V_t' is scaled volume of true crater. It is assumed that apparent crater radius and true crater radius are equal. V_t' is calculated as volume of a right circular cone frustum plus lower cavity hemisphere. R_c', lower cavity radius, R_a', and Dob' are frustum parameters.

[h] V_a' is scaled apparent crater volume, determined from preshot and postshot topographic maps of crater area for actual crater. Actual volumes are scaled to 1 kt by dividing by W in $kilotons^{0.88}$.

[i] V_{fb}' is scaled volume of fallback material or material which was placed in trajectory but landed inside crater; it is computed as $V_t' - V_a'$.

[j] V_e' is scaled volume of ejecta or material placed in trajectory which lands outside the crater. This is most easily available source of aggregate. An accurate determination of V_e is difficult. Apparent lip volumes from topographic maps must be used with supporting data from trenches cut through lip to determine volume of true lip. The simple approach used here is to assume a swell factor for V_{br} and to conserve this mass, or $V_e = (S)\ V_{br} - V_{fb}$. A swell factor of 1.65 is used for Pre-Schooner Delta and 1.45 for Danny Boy. In the absence of field data, S = 1.40 is used for all other craters.

[l] True crater radius, R_t has been estimated based on cross-section shown in Figure 4.

[k] V_e' shown for Neptune includes only material in slide area since approach used in note j is not applicable.