Modern Blasting Agents

Because they are safer, cheaper, and nontoxic, they are replacing dynamites in some operations.

Melvin A. Cook

More than 1000 million pounds of detonating explosives ("high explosives") are used annually in the United States in mining, quarrying, road and railway construction, seismic prospecting, submarine blasting, gas and oil-well shooting, and agriculture, as well as for such novel purposes as jet tapping of furnaces, jet piercing of casings and formations in oil wells, work hardening and forming of metals, and blind riveting (*1*). Until recently the most common explosives have been the dynamites invented by Nobel (donor of the famous peace prizes), which are based on nitroglycerine. But today, "blasting agents"—explosives which cannot be detonated by blasting caps but which require the use of powerful boosters—are rapidly replacing dynamites.

Types of Blasting Agents

The past four years have witnessed the introduction, first in open-pit and recently in underground mining, of several new do-it-yourself blasting agents, the most important of which is "prills and oil," a mechanical mixture consisting roughly of 94 percent fertilizer-grade ammonium nitrate (FGAN or, simply, AN) and 6 percent fuel oil.

A more recent series comprises the "slurry" blasting agents, which consist of coarse TNT and granular ammonium nitrate, and sometimes also sodium nitrate, dispersed in an aqueous solution of ammonium nitrate with only enough aqueous solution to give the mixture the consistency of thick soup. The success of the slurry blasting agents prompted investigations of still other types of slurry. In one type of nonexplosive sensitizers, for example, molasses (*2*), sugar, or heat-producing metals have been substituted for the TNT. In another, both the aqueous medium and the TNT have been replaced by a liquid medium—for example, methylamine or dimethylamine and ammonium nitrate—to accomplish both sensitization and fluidization. In a third type of slurry, TNT has been replaced by a heat-producing metal, such as magnesium, and the aqueous solution by Diver's solution (a mixture of ammonium nitrate and ammonia). While slurry blasting agents representative of each of these types have been used in boreholes of large diameter, none has been as successful as the coarse TNT types which already are being used in the United States and Canada to the extent of several million pounds monthly.

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Explosives composed of mixtures of ammonium nitrate and fuel (here *fuel* denotes any nonexplosive, combustible sensitizer) were first contemplated by Ohlsson and Norrbein in one of the earliest patents in the field of high explosives, and explosives of this type have been used extensively during the past quarter century. "Nitramon," the series to which the term *blasting agent* was first applied, is an example of the ammonium nitrate-fuel system. While such explosives have long been recognized as the cheapest source of explosive energy in the modern world, their great economic advantages were not fully realized until the discovery of prills and oil. Plant-formulated and packaged compositions almost identical to prills and oil—for example, one grade of Nitramon—have been in use for many years, but they did not lend themselves to field mixing. Field mixing is readily accomplished with prills and oil, owing to the unique properties of prilled ammonium nitrate, and as a result, savings of up to 75 percent of previous powder costs have been realized.

The field formulation of prills and oil became possible with the invention of the coarse, porous, kieselguhr-coated, "prilled," fertilizer-grade ammonium nitrate. This material was first manufactured as a fertilizer with special wax coatings to prevent caking, but after the great Texas City disaster and similar ones in Brest, France, and in the Black Sea region, caused by the hot bagging of organic-coated, prilled AN, the fertilizer industry turned for reasons of safety to the inert, inorganic, diatomaceous-earth coating. It was the unique absorptive properties of kieselguhr-coated, prilled ammonium nitrate for fuel oil that permitted the successful field mixing of prills and oil which began in 1955 on the Mesabi Iron Range (*3*). Prilled FGAN containing 3.5 percent kieselguhr absorbs rapidly and uniformly without mechanical mixing, but simply by diffusion, up to 6 percent fuel oil, fortuitously rejecting, to a large extent, any excess oil. At first the field mixing of prills and oil was accomplished by pouring into the borehole (around the boosters suspended on a Primacord downline) a bag of fertilizer-grade ammonium nitrate followed by a gallon of fuel oil and repeating until the desired total charge was in place in the borehole. To insure complete detonation, large dynamite or Nitramon primers or boosters were used either at the bottom and top of the shot (Fig. 1*a*) or at frequent intervals along the column (Fig. 1*b*), the boosters being detonated by the Primacord.

Borehole mixing did not prove reliable and soon gave way to surface mixing methods in which oil was sprayed into the ammonium nitrate as it flowed through a funnel or hose into the borehole (*4*) or was poured into open bags of FGAN, several hours or days being permitted for diffusion of the oil into the salt before the mixture was poured in the borehole (*5*). These methods in general depended on the unique ability of the kieselguhr-coated, prilled ammonium nitrate to absorb oil uniformly up to 6 percent and to reject any excess oil. With less absorptive types of ammonium nitrate, impractical products of excess oxygen and low strength generally result; with more absorptive types one must use an excess of oil, and these also yield an insensitive, low-strength product but one deficient in oxygen. Even when one takes special precautions to introduce the right amount of oil into a nonabsorptive type of ammonium nitrate, the oil may not distribute itself uniformly in the nitrate with diffusion blending or spraying. The fine-grained types, which are also nonporous because of their high surface area, absorb the required oil in only part of the nitrate, thus causing non-uniformity of diffusion or spray blending. Recently the "Stengel process" ammonium nitrate, a high-density, nonporous type, has been successfully adapted to field mixing of the nitrate and oil through blending an appropriate particle size distribution of the salt (*6*). This technique is equally applicable, but has not yet been used, with other types of ammonium nitrate—for example, those types made by evaporation drying in a graining kettle ("graining kettle ammonium nitrate") or by spraying and drying in a blast of hot air ("spray-day ammonium nitrate") and high-density, nonporous, prilled ammonium nitrate, made by the prilling process but brought to dryness during instead of after prilling.

The need for careful mixing of prills and oil (especially since uncoated and organic-coated, prilled, and various nonporous types of ammonium nitrate have come into extensive use) is currently widely recognized, and many are turning to special mixing systems to obtain uniformly mixed material (*7*). One may easily recognize poorly mixed prills and oil by the characteristic reddish-brown fumes, in which the products of detonation are colored by excess oxides of nitrogen. One can be sure that products which generate these beautiful reddish-brown clouds will develop appreciably lower strength and pressure than uniformly mixed prills and oil.

Owing largely to its very low density (0.82 gm/cm^3), the prills and oil mixture is really a low-grade blasting agent. Yet its use in bulk where it completely fills a cross section of the borehole (loading density $\Delta = 1.0$), in contrast with packaged explosives, in which the loading density Δ is necessarily appreciably less than unity, has largely offset the disadvantages of low density (*8*).

Unfortunately, the prills and oil mixture is useful only in dry-hole blasting because it is incompatible with water; moreover, its low density prevents it from sinking in water even if it is used in water-tight bags. It was the need to extend field-mixing methods to wet-hole blasting and the idea "if you can't lick it, join it" that prompted the development of slurry (*9, 10*). Aside from water compatibility, the advantages of slurry as compared with prills and oil are its high density (twice the density of prills and oil), which permits it to be used at much higher bulk strengths with accompanying large savings in drilling costs (since fewer or smaller boreholes are required), and up to four times greater borehole pressures, affording much better rock breakage at the bottom of the borehole where breakage is most difficult. Many operators are therefore using slurry even for dry shooting, especially where the rock is hard and difficult to blast and where drilling costs are high. Slurry made with half again as much coarse TNT as that used in formulations designed for holes of 4-inch diameter and greater (Table 1) and carefully oxygen-balanced—for example, by adjusting the ammonium nitrate-sodium nitrate ratio to obtain satisfactory "fumes"—is currently under study for use in underground blasting (*11*) in holes of small diameter (1.5 inch to 3.0 inches).

Blasting Methods

Major advances in blasting methods preceded the prills-and-oil breakthrough. Detonating fuse, first formulated with a lead-bound TNT core ("Cordeau"), became an important blasting accessory with the introduction of Primacord, a cloth- or plastic-bound detonating fuse containing a pentaerythratol tetranitrate core ranging in amount from 1 to 400 grains per foot. Primacord permitted the successful

Table 1. Some properties of the prills-and-oil, slurry blasting agents, and cast boosters as compared with dynamite and fine-grained TNT.

Property	Prills and oil (94/6)		Slurry		Cast boosters		TNT (fine)	Dynamite	
	Guhr AN	Organic-coated AN*	DBA-1†	DBA-2‡	"Procore" 3C	"Pento-Mex"		50% Forcite	75% Gelatin
Density									
ρ_1 (gm/cm^3)	0.82	0.88	1.52	1.68	1.7	1.65	0.87	1.4§	1.4
Detonation velocity *D* (km/sec)									
Theoretical	4.2	4.5	6.4	6.8	7.8	7.6	4.7		6.5
D (10 in. borehole)‖	4.05		6.15						
D (5 in. borehole)‖	3.57	3.05	5.17					5.1	
D (5 in. unconfined)#	2.77	2.67	4.9	5.8					6.5
D (1.25 in. unconfined)					7.8#	7.6	4.7	4.4	4.9
Strength									
A (kcal/gm) calc.	815	845	880¶	840¶	965	965	800	720	950
Seismic strength results#	814	850	870¶	860¶			(800)		
Detonation pressure									
p_2 (kbar) calc.	40	48	150	180	219	215	42		135
Aquarium method (5 in. unconfined)**	13.5		85	126	215 (3 in.)	220 (2 in.)	37 (1.5 in.)		
Borehole pressure									
p_i (kbar) calc.	18	21	75	90			22	49	60
Minimum booster (gm cast pentolite)#	40	5	80	10	††	‡‡	§§	§§	§§
Critical diameter d_c (in.)#	4	4	4	1.25	0.25	0.25	0.25		0.25
High velocity impact# sensitivity (kcal at 50/50 detonation-failure point)	130	15	>2500	500	130				<0.2

* The organic coating referred to here is the product sold under the trade name "Petro-Ag". It is used only to the extent of about 25 parts per million. † 60/15/25 AN/SN/coarse TNT. ‡ 32/32/36 AN/SN/TNT slurries with 10 to 20 parts water, 0.2 to 0.4 part guar gum and sometimes also 0.02 to 0.04 parts sodium borate. § *Blaster's Handbook* (Canadian Industries Ltd., Montreal, 1957). ‖ A, Bauer, *Rock Mechanics—Blasting Characteristics of Frozen Ore and Overburden* (Canadian Industries Ltd., Montreal, 1959). # Measurements by Intermountain Research and Engineering Co., Inc., Salt Lake City, Utah. ¶ Dry basis. ** A. Bauer and M. A. Cook (Institute of Metals and Explosives Research, University of Utah), unpublished. †† Cap sensitive (core only). ‡‡ Blasting cap. §§ Smallest blasting caps.

elimination from the borehole of blasting caps in large-diameter blasting; this was a great advantage from the standpoint of safety, Primacord being relatively much less hazardous than blasting caps, owing to (i) the use of a less sensitive explosive and (ii) the protection afforded the explosive core by the soft, pliable sheath. Moreover, the use of Primacord greatly simplified and facilitated the loading of large, multiple-hole blasts.

"Millisecond-" or "MS-delay" blasting, introduced more than a decade ago with the "Rockmaster" system of the Atlas Powder Company, provided an accurately timed, sequential blasting system. It was based at first on instantaneous caps fired in proper sequence and at appropriate (10- to 30-millisecond) intervals by special delay switching methods. Its early success led later to the development of special millisecond-delay blasting caps and still later to convenient millisecond-delay Primacord "connectors" or relays (see Fig. 2). Millisecond-delay blasting resulted in significant reduction in powder requirements, improved fragmentation, and marked reductions in seismic wave intensities; seismic waves from large blasts may become quite disturbing in surrounding residential and industrial areas when large multiple-hole blasts are fired without the use of the millisecond-delay methods (*12*).

Detonating systems for large, multiple-hole blasting were finally completely streamlined with the introduction in 1956 of a "ridiculously" small (160 gram) cast Pentolite booster (50 percent trinitrotoluene, 50 percent pentaerythratol tetranitrate) in place of the earlier very cumbersome booster systems (*13–15*). Slurry and the prills and oil mixture can be detonated with as little as 40 to 80 grams of cast Pentolite. Moreover, with the 160-gram cast Pentolite booster, one may tolerate appreciable deviations—for example, at least ± 3 percent—from the desired 6 percent of fuel oil in prills and oil, sensitivity usually dropping appreciably as the oil contact drops below 3 or increases above 9 percent. Consequently, this booster, now marketed by Canadian Industries Limited under the trade name "Pento-Mex," proved entirely adequate, much to the amazement of old-timers, and effected savings sometimes of 90 percent or more in booster costs.

The advantages of cast boosters are: (i) superior boostering action, (ii) superior water resistance (actually they are perfectly water-resistant), and (iii) unexcelled safety features, safety being of vital importance in boosters because they are usually the most dangerous elements in a large blast; the only blasting caps needed are attached after the charge has been loaded and the area has been cleared for firing. Unfortunately, only the most sensitive cast explosives, such as Pentolite, detonate with Primacord, at least in the economical (40- to 60-grain/ft) sizes. By taking advantage of this situation and the high *brisance* of Composition B (55.5 to 59 percent of cyclonite or RDX, 40 to 42 percent of TNT, and 1.0 to 4.5 percent of special organic coating agents), the superior "Procore" boosters were developed (*13–15*). The Procore booster comprises a Primacord-insensitive main booster charge and a Primacord-sensitive (protected) inner core of Pentolite or pentaerythratol tetranitrate, which fires the main charge.

Blasting systems based on Procore or "Pento-Mex" boosters in systems of the type illustrated in Fig. 1*c* comprise the most reliable, safest, and cheapest detonator systems for blasting agents in the modern industry.

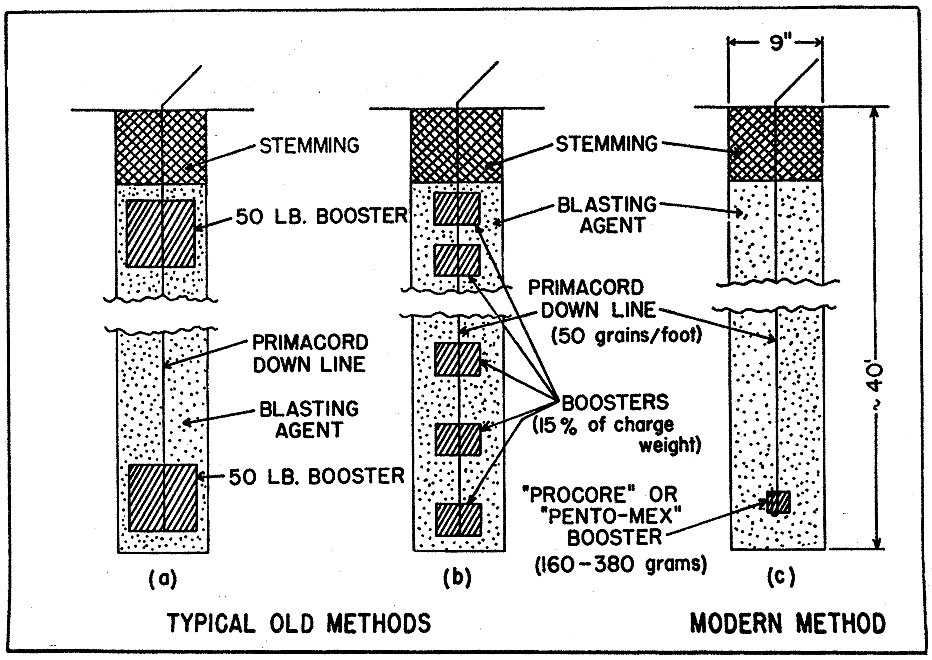


Fig. 1. Diagrams of loaded well-drill holes.

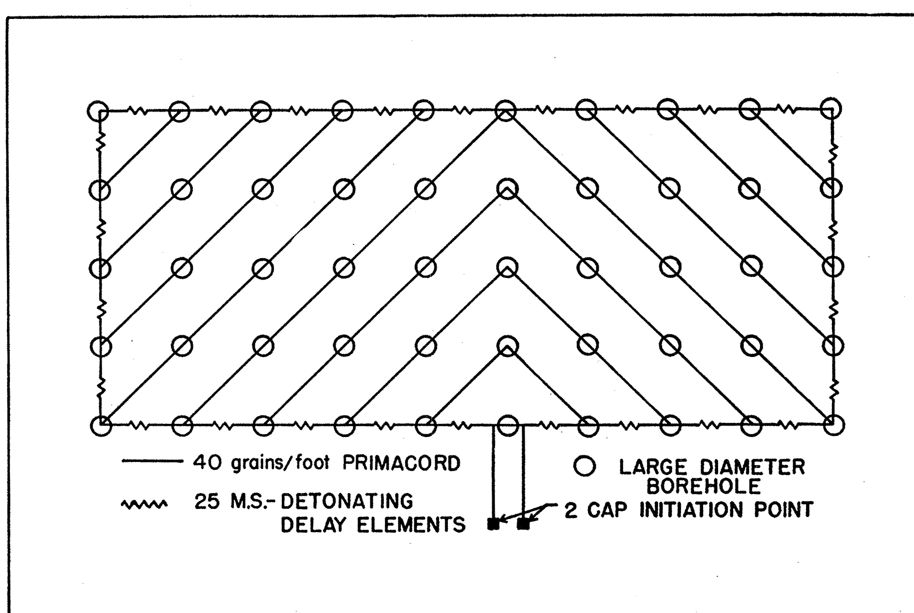


Fig. 2. Typical patterns in multiple-hole blasting.

Characterization of Blasting Agents

Explosive properties important in blasting are (i) detonation velocity D, (ii) "strength," or maximum available energy A, (iii) borehole pressure p_i, (iv) detonation pressure p_2, and (v) sensitivity.

Detonation velocity has long served, in lieu of a more fundamental criterion, as the criterion of intensity of the explosive. Explosives having the highest detonation velocity usually develop the highest *brisance* or shattering action, the property needed in blasting extremely hard rock; those of low detonation velocity are usually nonshattering and adaptable for blasting soft rock and for producing block stone and lump coal. Low-velocity explosives of high strength generally develop good *heaving action,* a term used to imply low but sustained pressure. There are well-known exceptions to these rules; the detonation velocity is merely a useful approximate criterion of the important intensity property of the explosive; it is not always a reliable criterion, especially for widely different types of explosives. Sometimes this is simply because the velocity measured in the laboratory is somewhat different from the real borehole velocity. (The measured velocity D may be much lower than the ideal hydrodynamic or theoretical maximum velocity D^*; moreover, it usually increases relatively rapidly with diameter and confinement, especially in blasting agents.) In other cases the detonation velocity is an unreliable criterion for a more fundamental reason. The more fundamental intensity property characterizing a blasting agent is its borehole pressure p_i—that is, the peak pressure developed in the borehole (*16*). The pressure-time curve of the explosive in borehole blasting is characterized by (i) the intensity property, borehole pressure p_i, and (ii) the extensity property, maximum available energy A. Together, these properties determine, along with loading conditions, how rapidly the pressure drops from the peak pressure p_i to the final effective pressure p_f where it ceases to do useful work.

The detonation pressure p_2 is defined hydrodynamically by the equation

$$p_2 = \rho_1 DW + p_1 \qquad (1)$$

where ρ_1 is initial density, W is particle velocity, and p_1 is initial pressure (usually completely negligible). The density ρ_2 in the compression part of the detonation wave is 1.25 to 1.4 times the initial density ρ_1. Therefore, p_2 is roughly twice as great as the "adiabatic" or "explosion" pressure p_3—namely, that hypothetical pressure which would be developed by explosion at constant volume and without heat loss to the surroundings. The borehole pressure p_i is identical to the adiabatic pressure p_3 when the loading density Δ is unity, but when Δ is less than unity the borehole pressure is less than p_3, pressure being very sensitive to density. The borehole pressure p_i may be defined simply as the adiabatic explosion pressure at the (effective) density $\rho_1\Delta$. With the borehole-pressure concept one allows automatically for free expansion from the volume ρ_1^{-1} per unit mass to the volume $(\rho_1\Delta)^{-1}$ per unit mass, realizing that in free expansion no useful work is done, useful work being accomplished by the explosive only in direct application of pressure against the burden.

Velocity usually varies approximately linearly with density as follows:

$$D \doteq a + b\rho_1 \qquad (2)$$

a and b being constants depending on the explosive and its D/D^* ratio. The approximations $W/D \doteq 1/4$ and $p_3/p_2 \doteq 0.5$ are reliable only within about 20 percent, but a useful approximation at $\Delta = 1.0$ is

$$p_1 = (D^3 - aD^2)/4b \qquad (3)$$

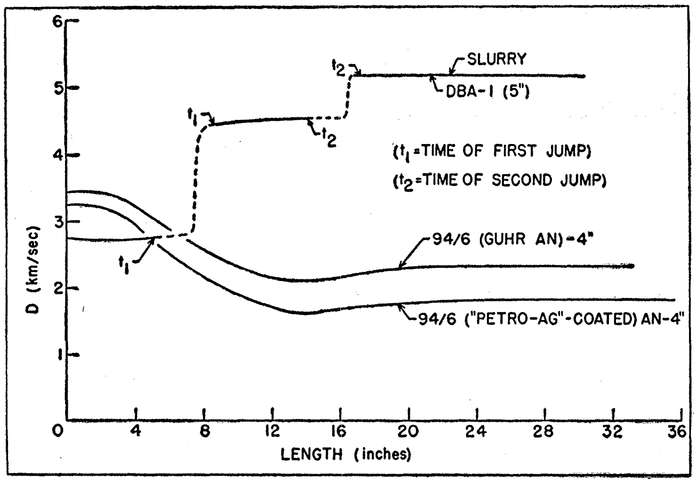
Therefore, only within the limitations of Eq. 3 is the velocity a suitable criterion of the more fundamental borehole pressure, but it is in any event clearly more complicated than a simple linear one in D. The velocity criterion, moreover, does not take proper account of the influence of loading density, Eq. 3 applying only when $\Delta = 1.0$, and even then only as an approximation.

Today, the use of velocity as the criterion expressing the intensity property of the explosive is considered not only ambiguous but unnecessary because the truly fundamental borehole pressure criterion may be applied rapidly, accurately, and reliably upon purely theoretical grounds. For this purpose one employs velocity data, not as a blasting criterion, but in determining the necessary equation of state of the products of detonation (*17, 18*). Indeed, studies based on the thermohydrodynamic theory of detonation (*1*) have already established a general (although empirical) equation of state for high explosives from which the two main blasting criteria, borehole pressure and strength, may be accurately computed for any explosive without even knowing its detonation velocity (*1*).

Quite aside from a blasting criterion, observations of detonation velocity provide extremely useful information for gauging the performance of an explosive. For instance, one may use variations with diameter of the ratio of observed velocity D to ideal velocity D^* to predict the rate of chemical reaction in detonation (*17*), frequently an important factor in explosive performance. Figure 3 illustrates some velocity transients recorded by a fast electronic oscillograph with prills and oil in 4-inch and slurry in 5-inch unconfined charges, using the "Pento-Mex" booster; knowledge of such transients is of great value in the selection of the appropriate booster and in the design of the blasting agent. Instructive, also are results of modern ultra-high-speed and rotating-mirror framing and "streak" photography of these effects. Figure 4 shows some distance-time results (the slope gives velocity) revealing the influence of different boosters for prills and oil. Note that the *heavy* (400 grain per foot) Primacord boostering of prills and oil is unreliable and inferior; the wave starts out from the Primacord boosters at phenomenally low velocity and picks up only very sluggishly, if at all. In contrast, the "Procore" 3C booster (380 grams) initiates the prills and oil right at its steady-state velocity, without an intervening transient. A striking result shown in Fig. 4 is that the Procore 2A booster, weighing only 160 grams, initiates prills and oil even more effectively than a charge four times larger of the very powerful 75-percent gelatin dynamite.

Modern, ultra-high-speed electronic oscillograph methods have recently been applied to measure detonation velocity in the borehole itself (*19, 20*). The most valuable result obtained from these studies was the finding that the ratio (D/D^*) of the measured velocity to the ideal one was practically unity in large-diameter boreholes for most of the blasting agents (Table 1). This result negates a great deal of effort that has been expended to increase the ratio D/D^* in prills and oil—for example, by the use of special coatings and careful particle-size control of the ammonium nitrate and by regulation of the oil content, sometimes to as low as 2 percent to achieve the maximum velocity and sensitivity in spite of the adverse effect on strength.

Strength, or maximum available



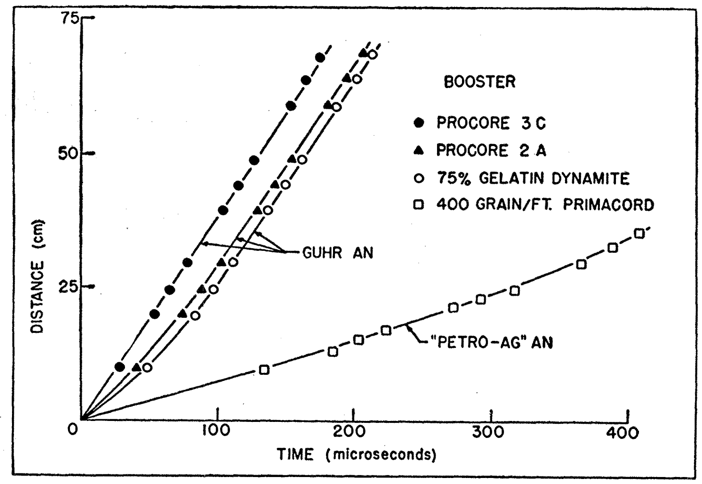


Fig. 3 (left). Velocity transients in unconfined prills and oil (94/6) and slurry with "Pento-Mex" boosters. Fig. 4 (right). Distance-time records in prills and oil (94/6) with different boosters.

energy A, may today be obtained accurately and reliably directly from theoretical computations. It is fundamentally defined by the work integral

$$A = \int_{v_i}^{v_f} p dV \qquad (4)$$

where v_i and v_f are the specific volumes in the initial and final states, respectively. Until recently, experimental methods for measuring strength in blasting agents were lacking, conventional methods for dynamites (the "ballistic mortar" and the "Trauzl block" methods) being not only inapplicable but of very questionable accuracy even for dynamites and of no value for blasting agents. Therefore, the recent development of two field-representative methods for measuring strength represent significant advances in the technology of blasting agents. These are a cratering method (*21*) and a seismic method (*14*). In each, strength A is measured for large charges at unit loading density underground—the condition encountered in practice; in the ballistic mortar one uses only 10 grams of explosive at a loading density of only about 0.04, and in the Trauzl block method the sample size is also only about 10 grams but the loading density is unity. The cratering method developed by Livingston is based on the determination of critical depth for cratering, the crater size as a function of charge weight, and the extent and velocity of "throw-rock," all being related in interesting and enlightening ways in the theory of cratering. Besides providing a measure of the strength A as a basic parameter, the cratering method also yields important information on rock fracture and adaptability of explosives in particular types of rock.

The seismic-strength method relates A to the portion of the total seismic wave energy recorded by the instrument at a fixed distance (preferably about 2500 feet) from charges of appropriate size (preferably about 25 pounds) fired at a fixed depth (usually about 3 feet) in a uniform medium. Appropriate media are water, sand, and uniform alluvium. For good reproducibility in alluvium, a deep, uniform formation should be selected and the same shot hole should be used repeatedly, test shots being fired alternately with calibration shots to eliminate effects of possible changing environmental conditions. For shots in water it is necessary only that the body of water be extensive enough that the banks and bottom do not shatter and undergo change during testing. Loose, fine-grained TNT provides an excellent, reproducible standard for calibration of the seismic-strength system and for reference purposes.

While it may not be obvious that the seismic-strength method is a true measure of strength, one may justify it as follows. (i) The measured total seismic energy varies linearly with the charge weight, as required by any suitable strength method (Fig. 5). (ii) Results do not depend on the density ρ_1 any more than to the extent expected from the theoretical variation of A with density, which is usually negligible, and

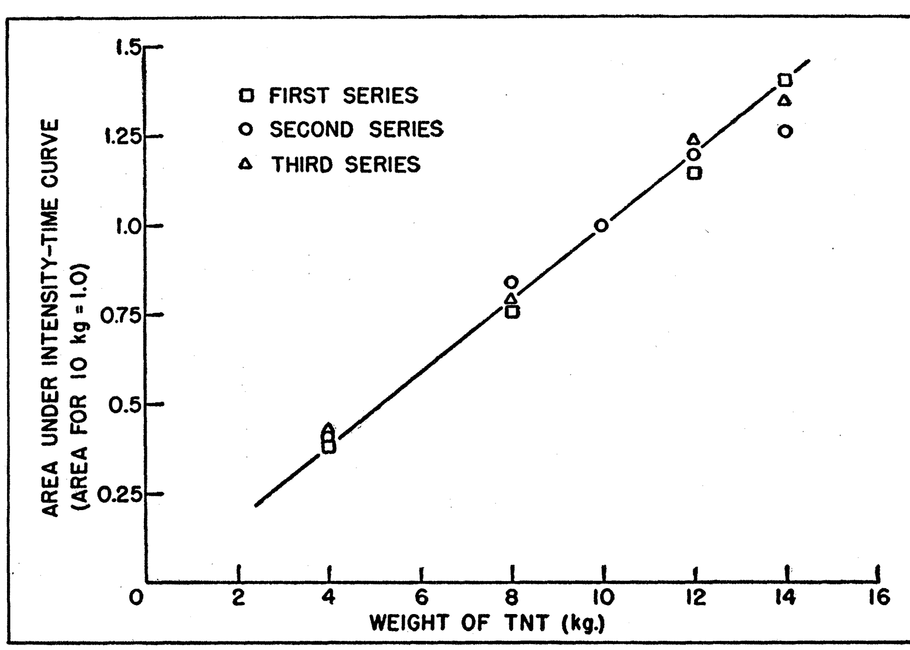


Fig. 5. Measured relative seismic energies for fine TNT at 0.9 gram per cubic centimeter.

they depend not at all on the detonation velocity D. (iii) Results compare favorably with computed relative strengths A/A_0, where A_0 is the strength of the TNT standard (Table 1). (iv) From the theoretical viewpoint it is sufficient to realize that under constant shot-hole conditions the ratio of seismic energy to total energy should remain approximately constant, and that because the geometry is fixed, the instrument records a constant portion of the total seismic energy.

The seismic-strength method has the advantage over the cratering method of relatively low cost and rapid application, but it yields no fundamental information on rock fracture.

Methods for measuring pressure have heretofore been completely lacking, owing to the formidable technical difficulties involved in measuring the extremely high pressures generated by explosives which, in some cases, may exceed 300 kilobars. The recent development of the "aquarium method" for measuring pressures thus represents a major technological advance (*22*). By this method one may now measure not only the detonation pressure p_2 but also high-intensity shock pressures in various media and possibly even borehole pressures, although the latter measurements have not yet been attempted. The aquarium method was recently applied to calibrate the "card-gap" test, the conventional "sensitiveness" test for monopropellants (*23*). In "sensitiveness" tests one measures the critical gap between a donor and a receptor yielding 50 percent detonations and 50 percent failures of the receptor, results in the card-gap test being expressed as the number of 0.25-millimeter plastic cards comprising the gap between the donor and the receptor charges at this 50/50 point. In the aquarium method one measures, by means of an ultra-high-speed streak or framing camera, the initial shock velocity V_w in water as the shock from the explosive, or a medium in question, enters the aquarium (see Fig. 6). The following well-established "impedance mismatch" equation may then be applied to compute, from the measured pressure p_w in water, the actual pressure p_m in the medium in question:

$$p_m = p_w\,[(\rho V)_w + (\rho V)_m]/2(\rho V)_w \qquad (5)$$

One must, of course, also measure the shock velocity V_m and density ρ of the medium and establish the relationship between the pressure p_w and V_w for water. The necessary calibration curves expressing the pressure-velocity relationship $p(V)$ for water have been established by observing, with the same (back-lighted) aquarium method, the velocity V and "free surface velocity" V_f (V_f is twice the particle velocity U) at the water free surface, with shocks of various intensities ranging from as low as 1 kilobar to above 140 kilobars (Fig. 7). In this method one also makes use of the hydrodynamic equation relating pressure to initial density ρ, shock velocity V, and particle velocity U—namely,

$$p \doteq \rho_1 V U = \rho_1 V\, V_f/2 \qquad (6)$$

Other transparent liquids or solids may also be used to measure pressures in this way; for example, calibration curves have also been established for Lucite, which has been used to measure pressures under conditions where the aquarium method cannot be applied. As a matter of fact, by immersing a charge or device in an aquarium, a high-speed framing camera can be used to establish accurately the pressure contours surrounding an entire charge of explosive or device (see Fig. 8) when the scale factor and framing rate of the camera are known.

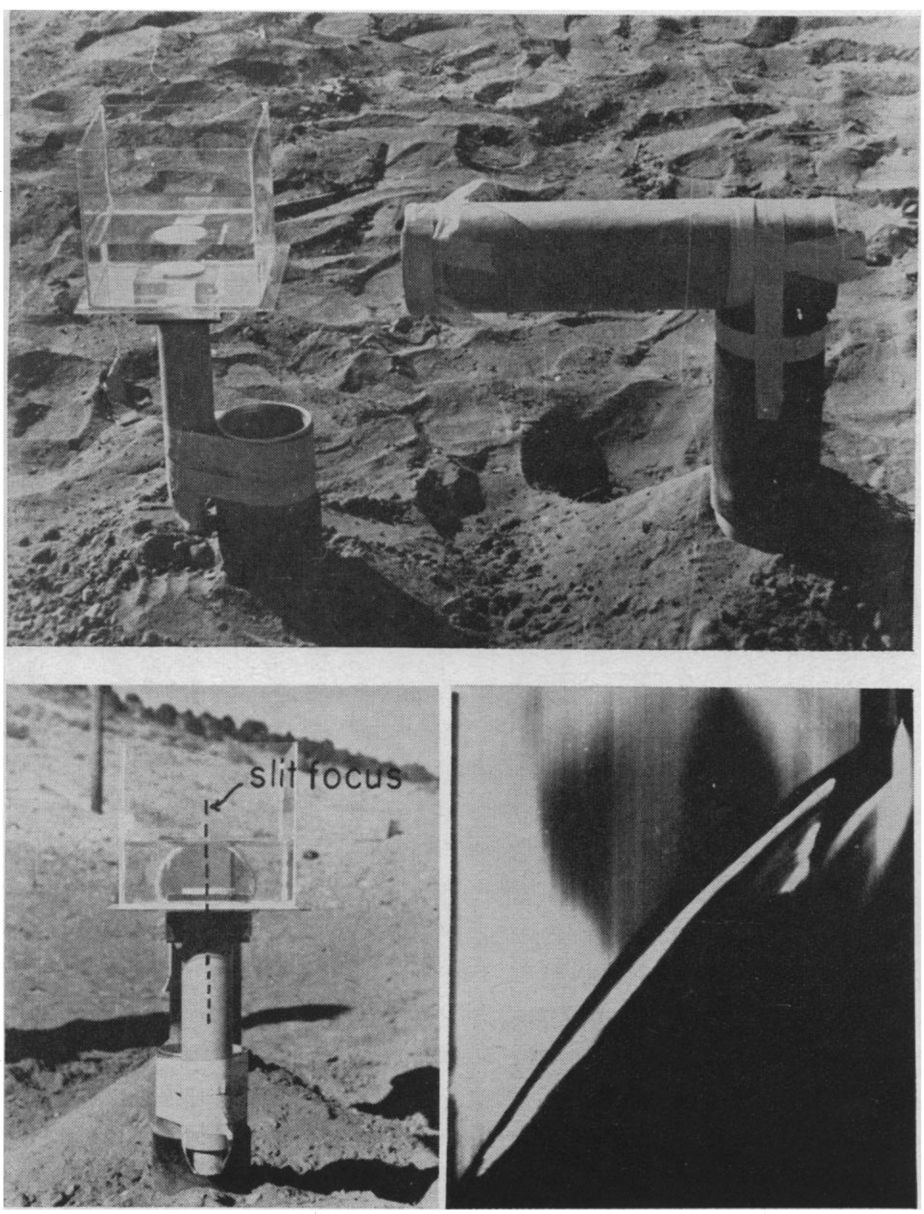


Fig. 6. The aquarium. (Top) Side view; light bomb at right; charge protruding into the aquarium. (Bottom left) End view. (Bottom right) Typical streak camera (time-distance) trace of shock wave in water.

Detonation pressure is the most significant property of a booster. For example, one requires only a tenth as much cast Pentolite (detonation pressure $p_2 = 215$ kbar) as loose TNT of density 0.9 gm/cm³ ($p_2 = 50$ kbar) and less than 0.25 as much cast Pentolite as 75-percent gelatin dynamite of density 1.4 gm/cm³ ($p_2 = 135$ kbar) to detonate prills and oil made with kieselguhr-coated, prilled ammonium nitrate. The influence of the detonation pressure is even more important in the boostering of slurry-type blasting agents.

Sensitivity is a vitally important factor in characterizing blasting agents. From a practical viewpoint, performance sensitivity and hazard sensitivity represent two quite different types of sensitivity and, indeed, require quite different experimental methods for their determination, the one measuring the reliability of performance and the other, the relative hazards involved in the formulation, handling, storing, and transportation of the blasting agent. The conventional performance-sensitivity test for dynamites is the air-gap "sensitiveness" test in which one measures the maximum air gap over which detonation will propagate by influence from a 1.25- by 4-inch ("half cartridge test") or a 1.25- by 8-inch ("whole cartridge test") donor to a like receptor. This test is useful in predicting the field performance of dynamites because cartridges may sometimes be separated by air gaps in the borehole. The "drop weight" or "impact" test is a familiar hazard-sensitivity test, suitable, however, only for testing dynamites and other sensitive explosives because only negative results are obtained with less sensitive types. In this test one determines the impact energy for 50 percent detonations and 50 percent failures of about 25 milligrams of explosive placed between small metal cylinders. Friction, heat, and shock sensitivity tests are also available, to evaluate the hazard sensitivity of sensitive explosives, but unfortunately none of these tests is applicable to blasting agents, since only negative results are obtained. It has, therefore, been necessary to establish whole new series of sensitivity tests for blasting agents (*9, 11, 14, 19, 24, 25*).

The applications of blasting agents dictate three types of performance-sensitivity measurements—namely, (i) the critical diameter d_c (the minimum diameter for uniform, consistent propagation), (ii) the minimum booster needed to detonate the blasting agent, and (iii) the large diameter gap "sensitiveness" in which the gap between a donor and receptor is, for example, an aqueous solution (*11*), dirt or other inert substance, or even air—material that might in practice interrupt the continuity of the explosive column. Critical diameter and minimum booster sensitivity tests have been used extensively in recent methods of studying performance sensitivity of blasting agents. The agents may be measured for charges in thin paper tubes six or more charge diameters in length or they may be measured under heavy (for example, steel) confinement. If a blasting agent can be detonated and propagated satisfactorily in a given charge diameter either bare or in a thin paper tube (such charges are referred to as "unconfined"), it will be expected also to perform satisfactorily in the same or larger diameter in the borehole, because the minimum booster requirement and the critical diameter both decrease as the degree of confinement is increased. For example, the unconfined critical diameter d_c and the minimum booster of prills and oil and large-diameter slurry are about 4 inches and 40 grams of cast Pentolite, respectively. On the other hand, these agents can sometimes be propagated in even 2-inch diameter when less than 20 grams of Pentolite are used as the booster. For this reason, to simulate a borehole confinement some prefer to carry out performance-sensitivity measurements in steel pipe (*19, 24*). On the other hand, while the critical diameter measured in pipe is usually considerably less than in a borehole, in one investigation the critical diameters measured for several mixtures of ammonium nitrate and fuel oil in soft ground agreed closely with those measured in unconfined charges but were appreciably greater than those obtained in steel pipe (*6*). This illustrates the danger in reliance upon results obtained under artificial confinement.

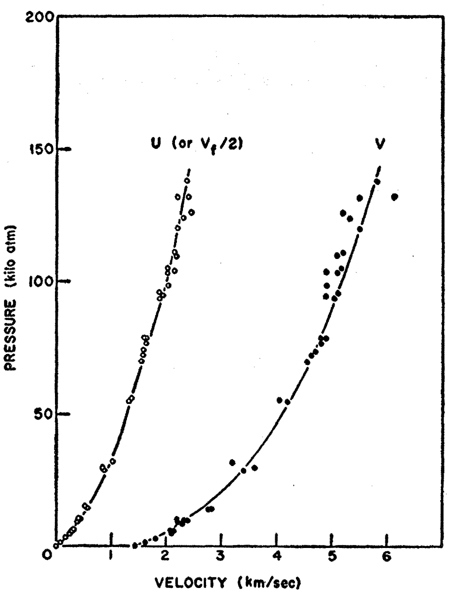


Fig. 7. Calibration $p(V)$ curves for water shock waves (*36*).

Measurements of the minimum booster sensitivity may be based on a uniform series of cast Pentolite boosters of different sizes. Some investigators, however, prefer to use different numbers of blasting caps in a bundle or different numbers of Primacord strips bundled together as the measure of the minimum booster sensitivity (*19, 24, 25*). It is good practice in any case to measure the minimum booster sensitivity in diameters at least 1 inch greater than the critical diameter to avoid confusing results with the ability of the charge to propagate. Also, one should use charges six or more diameters in length to make sure that the explosive actually reaches high-order detonation in a minimum booster sensitivity test.

If one were to rely on the measured critical diameter in unconfined charges as a measure of borehole performance, he would not, of course, attempt to shoot prills and oil in a diameter below 4 inches, irrespective of the type of ammonium nitrate used (*14*). Still, the prills and oil mixture has been shot satisfactorily in boreholes of smaller diameter (usually, however, of short length) by using several periodically spaced boosters. In some instances costly failures have resulted in attempts to use prills and oil in long boreholes 2 to 2.5 inches in diameter. On the other hand, the critical-diameter criterion of performance sensitivity for unconfined charges justifies the use of the more sensitive slurry types (see Table 1, DBA-2) in diameters as small as 1.5 inch, with only one small (1.25- by 1.50-inch) cast Pentolite booster in each hole. Indeed, this blasting agent has been fired satisfactorily in boreholes 1.5-inch in diameter and 150 feet long with but one small Pentolite booster.

The uniformly negative results obtained with blasting agents in conventional hazard-sensitivity tests is dangerous because it has led some to underestimate the hazards. Fuel-sensitized, fertilizer-grade ammonium nitrate is not itself without hazard, as emphasized by the great Texas City and similar disasters involving ammonium nitrate coated with about 0.75 percent of organic material. Moreover, the prills and oil mixture has actually been observed to explode spontaneously upon standing in large (stemmed) boreholes, owing to chemical incompatibility of prills and oil with certain contaminants which causes self-heating, ignition, and ultimately, spontaneous explosion. Clearly, moreover, the prills and oil mixture is quite as dangerous as dynamite when it is loaded in a truck together with dynamite, as was emphasized by the recent Roseburg, Oregon, disaster.

A novel high-velocity impact test has recently been developed as a positive hazard-sensitivity test for blasting agents (*11*). This test consists of hurling steel plates into charges of blasting agent (9 inches in diameter, 18 inches long) by means of Composition B charges of appropriate size and from a standoff distance of 20 feet. The sensitivity is expressed in terms of the kinetic energy of the impacting plate when 50 percent detonations and 50 percent failures result. For blasting agents, plate velocities should be in the range of 1.8 $\pm$ 0.5 km/sec; appropriate plate sizes fall in the range of 1 inch in diameter by 0.125 inch in thickness to 10 inches in diameter by 1 inch in thickness. This sensitivity is to be compared with that of dynamites, which may be detonated simply by the spit of a blasting cap at comparable stand-off.

Results obtained by the high-velocity impact method (Table 1) thus illustrate the vast superiority of blasting agents over dynamites as regards hazard sensitivity and show strikingly why dynamite tests are inapplicable for blasting agents, and vice versa. For instance, 60- and 75-percent dynamites detonated consistently (or nearly so) at impact energies of less than 0.2 kilocalorie, whereas prills and oil made with kieselguhr-coated ammonium nitrate detonated half the time at an impact kinetic energy of 130 kilocalories. This means that this blasting agent has a hazard sensitivity less than 0.001 that of dynamite (*11*). Another striking result was the fact that prills and oil made with an organic-coated, prilled ammonium nitrate had nine times higher impact sensitivity (15 kilocalories at the 50 percent detonation 50 percent failure point) than prills and oil made with kieselguhr-coated fertilizer-grade ammonium nitrate.

Slurry exhibited phenomenally low impact sensitivity, the large-diameter slurry (DBA-1, Table 1) failing to detonate at all with the exceedingly high impact energy of 2500 kilocalories; even the more sensitive, small-diameter slurry (DBA-2, Table 1) exhibited a 50/50 point of 500 kilocalories.

Illustrative of the great superiority of the cast boosters over the dynamite boosters, the Procore 3C exhibited a 50 percent detonation 50 percent failure point in the high-velocity impact test of 130 kilocalories, the same as for prills and oil made with kieselguhr-coated ammonium nitrate.

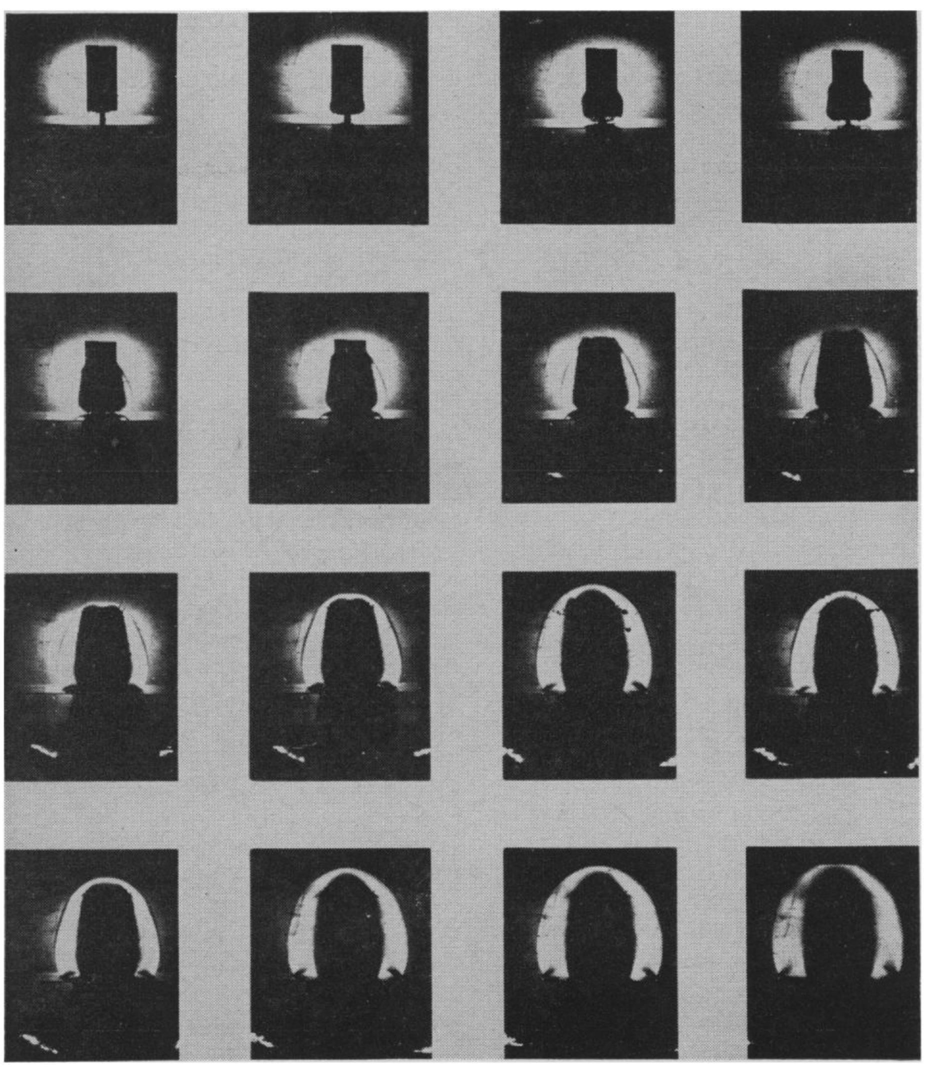


Fig. 8. Megaframe-per-second photographs of a cylindrical charge detonated in the back-lighted aquarium.

Rock Mechanics

Rock mechanics constitutes a vital, but too little investigated, facet of mining research. If the science of rock fracture were sufficiently developed it would be of great value in the operations of drilling, blasting, loading, and crushing of rock. Fortunately, a vigorous world-wide interest in rock mechanics has developed during the past few years, and already many highly beneficial results have been obtained (*21, 26–29*). Million-frame-per-second color photography of wave propagation and fracture in transparent solids has provided striking new fundamental information on the modes and mechanism of fracture of solids in impact loading by detonation and shock waves (*29*). Figure 9 shows such a sequence in Lucite, in which several types of fracture patterns as well as the behavior of interacting shocks are clearly evident.

One has to consider primarily three types of rock fracture: compression, shear, and tensile. Rock breakage is maximized in a blast when the blast is carried out in such a way that the frac-

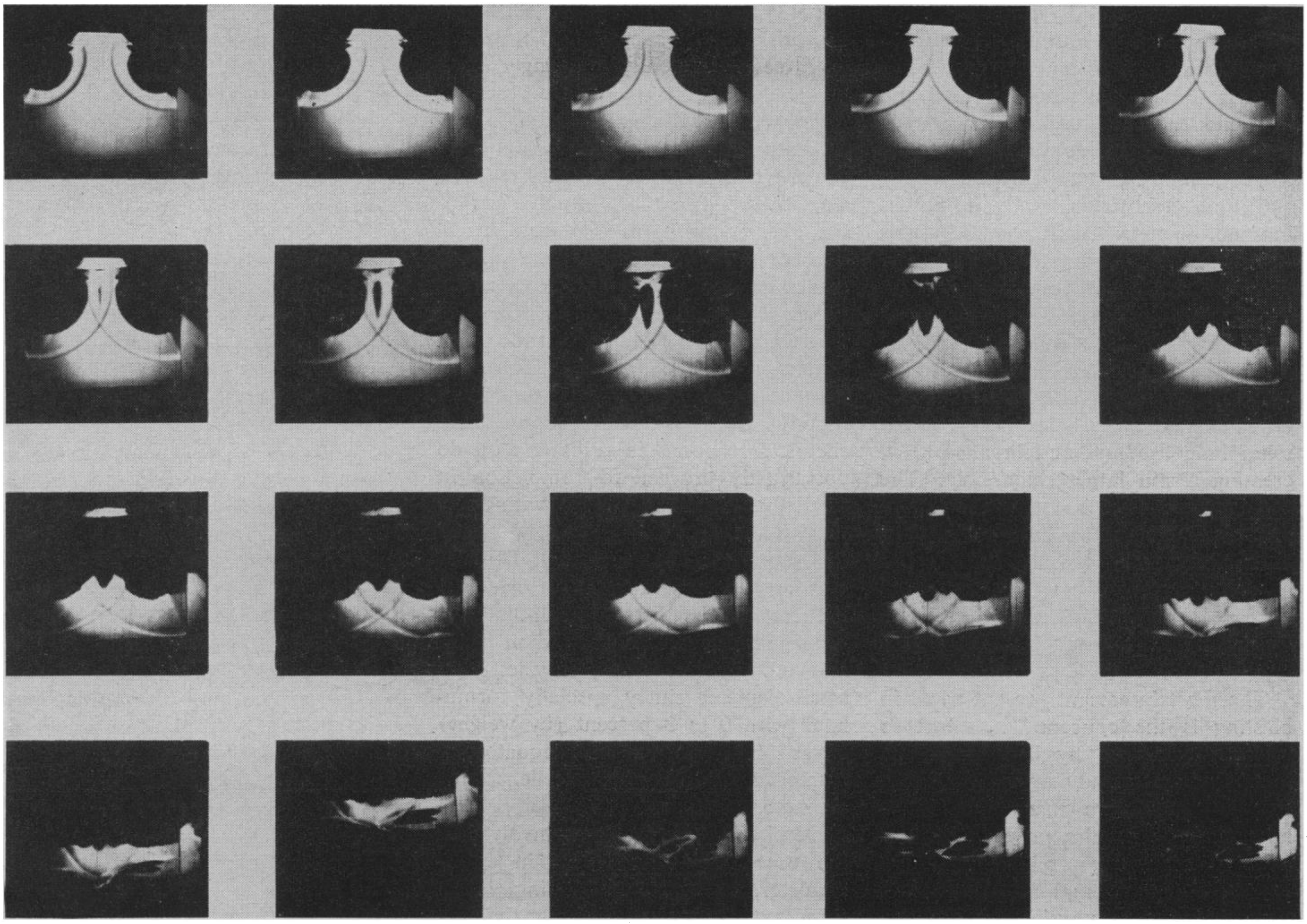


Fig. 9. Megaframe-per-second photographs of shock waves and fragmentation patterns in back-lighted Lucite.

ture is of the type which the rock is least able to resist. Generally, hard rock has very high compressive strength, moderately high shear strength, but relatively low tensile strength. For example, in a typical hard rock the ratios of compressive to shear to tensile strengths may be approximately 100/10/1. One expects, therefore, that the best breakage will occur under conditions where the tensile forces are maximized and the shear and compression forces are minimized. Often a new free face of a well-engineered blast shows a semi-borehole in the vicinity of which one observes very little evidence of rock fracture by compression. Since the borehole pressure p_i is much higher than the compressive strengths of rock recorded in the laboratory, the absence of appreciable compressive fracture in the vicinity of a borehole in a well-engineered blast confirms the belief of many that true compressive strengths of rock are much higher than those indicated by results recorded in the laboratory. Compressive strengths observed in laboratory tests are invariably complicated by artificial, circumstantial shear and tensile fracture incurred by the use of excessively small samples (*30*). Thus, in most hard-rock blasting one generally needs to consider only shear and tensile fracture processes. On the other hand, in the softer, more porous and pliable rock the shear and compressive strengths may be comparable in magnitude to the tensile strength, which then becomes a factor of chief concern.

Because of the usual high shear- to tensile-strength ratio of rock, much more energy is consumed in breaking under shear than under tensile forces. Furthermore, much stronger seismic waves develop, because the intensity of a seismic wave is determined largely by the ultimate strength of the rock (*28*). Herein lies much of the secret of the success of millisecond-delay blasting. In other words, the elimination of shear forces, permitting the rock to break under tension, is no doubt responsible for the appreciable effectiveness of the millisecond-delay blasting.

At least two types of compression waves are generated by the blasting agent: (i) the initial shock wave, which is simply a continuation of the detonation wave, the reflection of which at the free surface produces fragmentation whenever the tension in the reflected tensile wave exceeds the tensile strength of rock, and (ii) a much broader and enduring compression "wave" in which breakage ultimately results either in shear fracture or in what may be called rock bursting, a type of "release-of-load" fracture (*27*). When shear and tensile forces cannot develop, the rock is first compressed and remains under compression for a relatively long time after the initial shock wave has passed, owing to the prolonged application of pressure by the detonation gases. When eventually this compression is relieved as the pressure in the gases drops to a critically low value, the energy stored through compression will usually result in ultimate explosion of the rock. Millisecond-delay methods have the effect of uncoupling the burden of one shot hole from that of the adjacent ones, so that the desirable tensile wave and release-of-load, or rock-bursting, type fractures may predominate over the more costly shear-type fracture.

Tensile fracture is vitally important in small-diameter "drift rounds." This is perhaps best illustrated by the success of the popular "burn cut" round, in which one provides a sizable open relief hole—that is, an empty hole of 2- to 4-inch diameter—at the center of the burden (*31*). The round is then timed so that those holes closest to the relief hole fire first and break into it, creating a still larger relief hole. The next nearest holes are then fired, and so on until the entire burden has been broken, largely by tensile fracture.

Future Developments

The most important present trend in blasting is the concentrated effort to replace dynamites by blasting agents in small-diameter, underground mining. Problems here are manifold. Dynamites usually require no boosters but merely blasting caps or Primacord fuse to detonate them and are ideal from the standpoint of physical texture and ease of handling, in which respect they will probably never be excelled. But in addition to being extremely hazard-sensitive, both the explosive itself and (usually) its products of detonation are quite toxic. Blasting agents are much more difficult to handle because they require special boosters, have less desirable physical characteristics, and require special loading techniques because of their marginal performance-sensitivities, particularly in small-diameter boreholes. Their great advantages are (i) low cost, (ii) nontoxicity (this may not apply as far as their "fumes" are concerned), and (iii) low hazard sensitivities. Booster requirements of blasting agents for small-diameter use can be met only by careful control of sensitivity, permitting the use of minimum, yet adequate, boosters, because booster costs become critical in small-size charges. Equally difficult is the "fume" problem; the noxious products of detonations, primarily carbon monoxide, the oxides of nitrogen, NH_3, HCN, and so on, may sometimes become very dangerous in underground mining with some types of blasting agents as well as with some dynamites. The Bureau of Mines is currently devoting considerable research effort to the study of fume problems in prills and oil. Results to date (*32*) show that bad fumes result largely from reaction sluggishness, due mainly to the use of the blasting agent in diameters below its unconfined critical diameter and to inadequate boostering. Theoretically, fumes should be excellent in prills and oil when the nitrate-oil ratio (by weight) is 94.5/5.5. Actually, however, even at this ideal ratio the fumes are usually relatively poor because the chemical reactions in prills and oil do not usually proceed to completion in small boreholes, especially with marginal boostering.

Slurry adapted to small-diameter blasting appears attractive, evidently because it has better small-diameter propagation characteristics than prills and oil. Studies show, in fact, that small-diameter slurry specially formulated with 0 to 3 percent (by weight) oxygen deficiency and an adequate performance sensitivity has excellent fume characteristics.

Despite all the problems involved in the use of blasting agents in small-diameter, underground blasting, initial successes justify the belief that the next decade may witness the large-scale replacement of dynamites with the less expensive and much safer blasting agents.

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