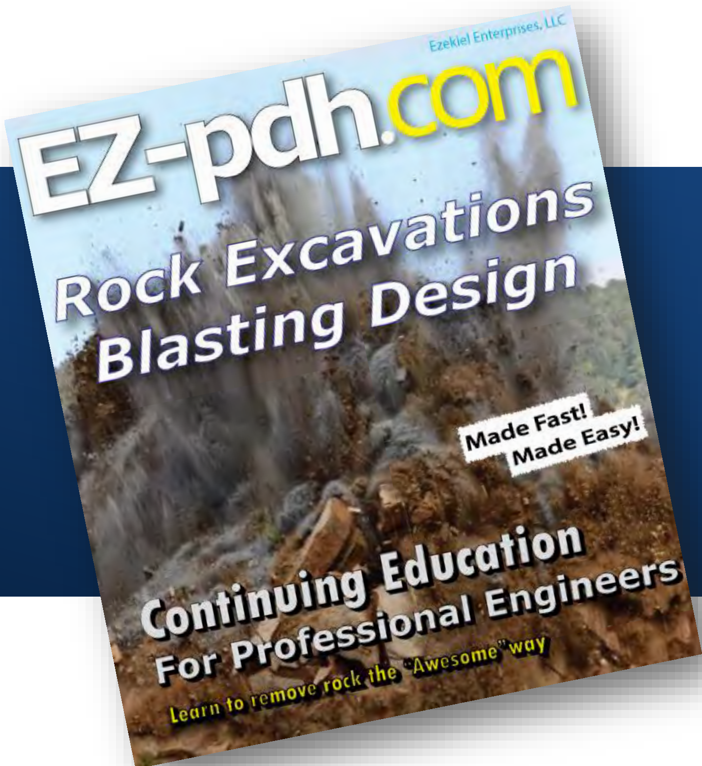

Rock Excavations Blasting Design Part 1

Six (6) Continuing Education Hours
Course #CV1240

Approved Continuing Education for Licensed Professional Engineers

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Course Description:

The Rock Excavations Blasting Design Part 1 course satisfies six (6) hours of professional development.

The course is designed as a distance learning course that enables the practicing professional engineer to understand the fundamentals of blasting for rock excavations.

Objectives:

The primary objective of this course is to introduce the student to the art and design of using explosives for removal of rock in excavations.

Grading:

Students must achieve a minimum score of 70% on the online quiz to pass this course.

The quiz may be taken as many times as necessary to successful pass and complete the course.

Table of Contents

History of Blasting.

Explosives have been used in mining and construction applications since 1627, the date of the first recorded use of black powder for rock blasting in a gold mine in Hungary. Before this, black powder was used primarily for military applications, signals and fireworks. The first recorded civil structure using black powder was the construction of the Malpas Tunnel of the Canal du Midi in France in 1679. Black powder remained in common use for construction and mining from the 1600s until the invention and application of nitroglycerine dynamite by Alfred Nobel in 1866. For much of that time, the composition of black powder remained unchanged with constituents of 75% saltpeter (potassium nitrate), 15% charcoal and 10% sulfur. Then in 1858, an American industrialist, Lammot du Pont began making sodium nitrate powder, a less expensive alternative to potassium nitrate-based powder, but its use was curtailed after the invention of dynamite. Both were less effective in rock blasting than dynamite, which quickly super-seded the older blasting technology.

Nitroglycerine, invented by the Italian chemist Ascanio Sobrero in 1847, was notoriously unstable, could explode when jolted, and was extremely sensitive to heat, sparks, or other ignition sources. Its power and ability to remain viable when wet were distinct advantages over black powder, thus it was used for excavation of some of the hardest rock along the U.S. trans- continental railroad under construction in the 1860s. State laws on transport necessitated manufacturing on site, and it remained considerably more dangerous than black powder.

The invention of the blasting cap, by Alfred Nobel in 1864 and the stabilization of nitroglycerine through the use of diatomaceous earth changed this situation. Nobel's dynamite al- lowed the easier transportation and more controlled initiation of blasting than could be achieved with nitroglycerine alone and was intended for use in mining and construction. In the United States, dynamite came into common usage after 1867 when Nobel licensed his process to a U.S. manufacturer. It became the first "high explosive" used in commercial blasting and saw its first large scale use in the construction of Hoosac Tunnel in 1876. Nobel went on to patent gelatin dynamites in 1875. Trinitrotoluene (TNT) was also developed in 1863 by Joseph Wilbrand as a yellow dye, but it was not used as an explosive for many years after its invention due to its high activation energy. It is less powerful than dynamite and has primarily been used as explosive ordinance. Dynamite remained the explosive of choice in construction and mining until 1956 when Robert Akre patented a lower cost alternative called Akremite that was made from ammonium nitrate and coal dust.

Later diesel oil was substituted for the coal dust, ammonium nitrate and fuel oil (ANFO) has stayed in common use since that time for rock blasting due to its stability and low cost. As of 2012 ANFO is by far the most commonly used explosive in North America. Other developments have expanded the blasters' toolbox since the development of ANFO with newer explosive products such as slurries, water gels, and emulsions.

Slurries and water gel explosives were invented by Dr. Melvin Cook in 1956 and was an alternative to ANFO in wet blastholes. Later emulsion explosives (1969) were developed by the blasting industry.

Developments in detonation cords, electric delay detonators, and shock tube detonators have further widened the available tools and techniques that can be used to fragment rock and better control the effects of blasting.

Basic Blasting Terminology.

A complete glossary is included in the appendix of this course. However, since the next several sections will use many of the terms listed here in their technical senses, this section is provided as a quick review for those readers who are beginning the study of blasting, or for those who need a refresher.

Explosives are chemical mixtures or compounds that, when subjected to shock, impact, or heat, produce a rapid chemical reaction, accompanied by a shock wave in the product, that results in the sudden release of energy through the process of detonation. This sudden release of energy, mostly in the form of hot gas, when properly confined and initiated, can be used to per- form mechanical work on the surrounding material. There are four basic components in commercial explosives: carbon, hydrogen, nitrogen, and oxygen. These components are combined so that the explosive mixtures are part oxidizer and part fuel or sensitizer (Figure 1).

Oxidizers	+	Fuel	=	Explosives
Ammonium Nitrate (AN)		Fuel Oil (FO)		ANFO
Potassium Nitrate (saltpeter)		Sulfur and Charcoal		Black Powder

Figure 1. Example Formulations of Two Common Explosives.

Combustion is the exothermic chemical decomposition of a compound. It is a reaction between a fuel and an oxidizer.

Detonation occurs when the combustion of the explosive compound occurs more rapidly than the speed of sound. It propagates through the explosive material by a detonation, or shock wave. The speed of this wave through the surrounding rock will vary by explosive used, proper- ties of the rock, and appropriate design of a blast.

Detonation Velocity is the speed that the detonation travels through the explosive once it has reached a steady state velocity.

Deflagration, or burning, occurs when the combustion of the explosive compound occurs at less than the speed of sound. It propagates through the explosive material through a flame front (heat transfer) with no shock wave.

Blast Design and Physical Layout of Explosives.

Rock Blasting is usually achieved by the drilling of holes into the rock. These holes are spaced to achieve the appropriate rock fragmentation, shearing, and heave needed for the project. Several common terms are used to refer to the blast design and physical layout of the explosives and holes. Rock blasting is the science and art of the use of controlled explosive energy to fragment, displace, and shear — thus facilitating the removal of rock. It can be used both for surface and subsurface rock excavation and for rock removal underwater. When this explosive energy is released inside rock, it produces both fragmentation of the rock and heave (displacing the rock from its in-situ condition). Blasts can be designed to fragment rock only for ease of removal, but can also be designed to fragment rock into smaller sizes useful for the production of rock products such as rip-rap.

Backbreak and Overbreak are fairly self-explanatory terms that denote rock breakage beyond the intended limits of excavation. In some usage, these terms are distinguished in that "backbreak" refers to fracturing beyond the limits of excavation, "endbreak" refers to fracturing beyond the edge or side limits of the blasting pattern, and "overbreak" refers to the actual removal of rock beyond the intended limits of the excavation.

Boreholes are holes drilled in rock into which explosives are placed (Figure 1-2). These are generally drilled using "destructive" drilling techniques that do not leave a rock sample such as core behind.

Burden is the volume of rock to be fragmented and displaced by blasting. There are two kinds, the drilled burden and the shot burden. (Figure 1-3) Illustrates this and next four terms.)

Drilled Burden is defined as the distance between a row of boreholes and the nearest free face. It is always measured perpendicular to a row. It is also the distance between any two rows of boreholes. When laying out a blasting pattern for a shot, this is the term usually meant when using the word "burden."

Figure 2. Empty Boreholes on a Regularly Spaced Pattern.

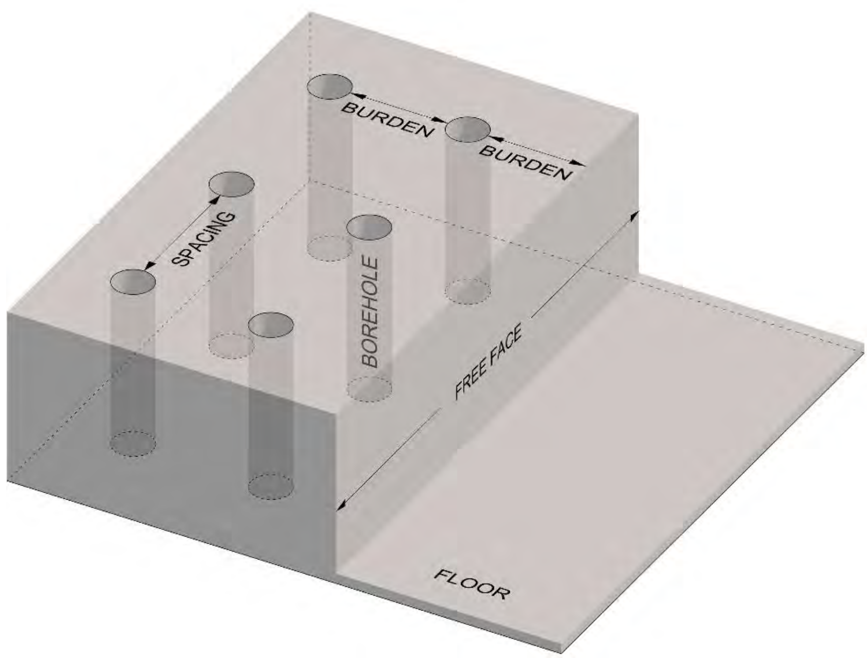

Figure 3. Blasting Layout Terminology.

True Burden is defined as the perpendicular distance between a single borehole containing explosives and the nearest free face.

Spacing is defined as the distance between holes that are located in a row. Drilling pat- terns are always defined as this spacing and the burden and spacing (e.g., for a 5 x 6 pattern, the blast design has a burden of 5 ft and a spacing between boreholes of 6 ft).

Relief is the presence of a free face in the rock mass such that the blasted rock can dis- place into that space as it heaves and expands due to the detonation. It can be a ledge or bench face or an internal face created by previous holes firing.

Free Face is defined as the nearest open face or relief. In rock blasting, this is at the edge of the rock face or relief created by previously fired blastholes. It is also the top surface of the rock that will be blasted. Features such as joints, faults, bedding planes, voids, and other dis- continuities are not considered free faces because they do not allow for relief.

Decking is a method to create unloaded zones in an explosive column in a blasthole. “Decks” are often created by using stemming to separate several layers of explosives in a loaded hole. Decks may be used to increase the efficiency of the blast, to limit the amount of explosives at any given delay, or to accommodate a weak layer or void that has been encountered in the rock. Air decks are unloaded portions of the explosive column that contain no explosive or stemming materials.

Depth of Advance (underground blasting) is the total length of the borehole that broke from the formation or the distance a blaster wants to break down to the intended grade of the blast.

Stemming is the inert material put in a borehole to provide confinement along the axis of the borehole. Material used for stemming is commonly small sized crushed aggregate (Figure 1-4). Note that Corps’ practice generally forbids the use of drill cuttings as stemming.

Subdrill is the length of borehole drilled below finished grade or the bottom grade of the intended blast.

Swell is the term used to account for the increase in volume of rock that has been blasted or otherwise excavated. The volume increases from the in-situ or in-bank condition be- cause the piled rock fragments take up more space after the blast because when there is consider- ably more void space between the rock boulders and fragments than in the intact (pre-blast) condition.

Swell Factor is the percentage of increase in volume expected due to blasting or excavation.

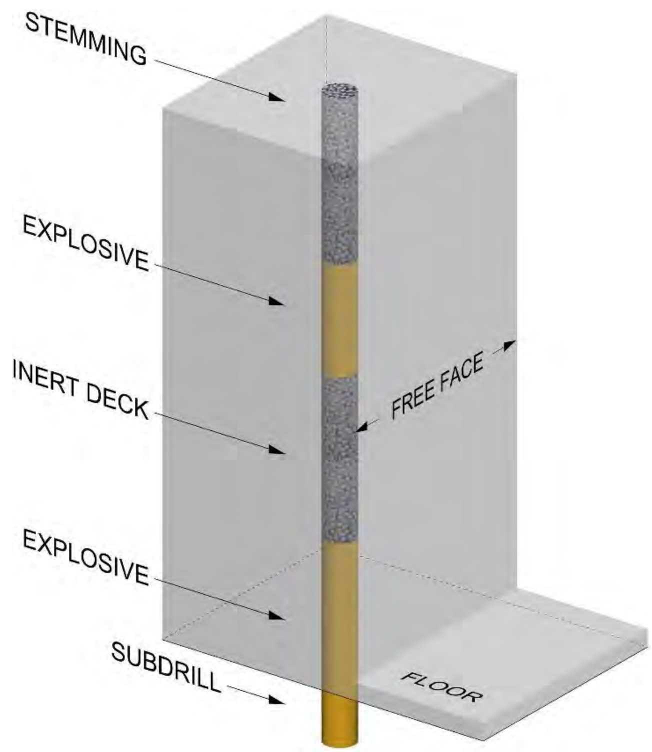

Figure 4. Borehole Explosive Layout Terminology.

Classification of Explosives.

There are a number of classifications schemes for explosives, but the U.S. Department of Justice Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) divides explosives into three categories based on the behavior of the material when unconfined:

Blasting Agents are high explosives that are less sensitive to initiation and cannot be detonated using a No. 8 strength blasting cap. These are also called "booster sensitive" or "non- cap sensitive" explosives. They require a booster to detonate. The most common blasting agent is ANFO.

Low Explosives are an explosive material that deflagrates (or burns) at a high rate of speed when unconfined. The most common example is black powder.

High Explosives are highly sensitive explosives that when unconfined can be detonated using a No. 8 strength blasting cap. A high explosive detonation is accompanied by a shock wave moving through the explosive. Dynamite is a type of high explosive.

Parts of Blasting Systems.

Blasting Caps are small, sensitive explosive devices that are generally used to transmit the detonation signal into a blasthole and detonate cap sensitive explosives. Blasting Caps can initiate instantaneously or can contain delay element so that the cap fires at a predetermined de- lay time in milliseconds.

No. 8 Blasting Cap is an industry standard blasting cap used as a detonator (Figure 1-5). It contains two grams of a mixture of 80% mercury fulminate (a secondary explosive) and 20% potassium chlorate (a primary explosive), or a blasting cap of equivalent strength. An equivalent strength cap comprises 0.014-.016 oz of pentaerythritol tetranitrate (PETN) base charge pressed in an aluminum shell with bottom thickness not to exceed 0.03 in., to a specific gravity of not less than 0.81 oz/in^3, and primed with standard weights of primer depending on the manufacturer. It is the most common type of blasting cap in use as of 2016.

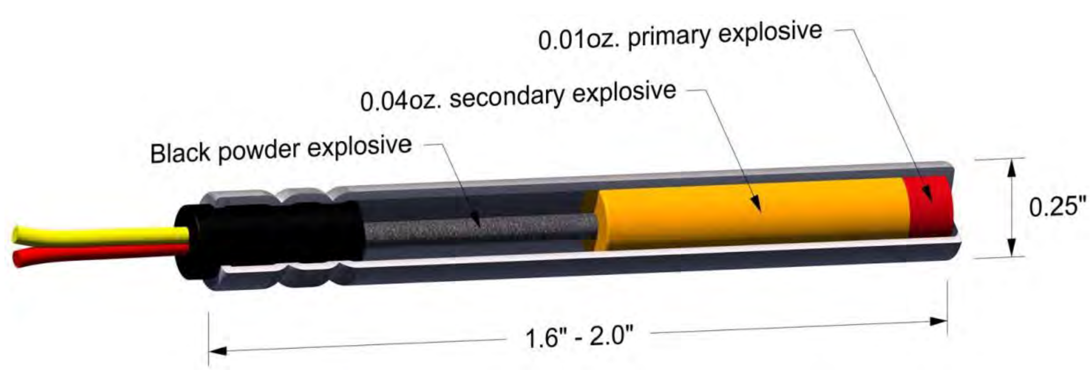

Figure 5. Example of No. 8 Blasting Cap.

A Booster is a sensitive, high energy, charge that can be used to set off a less sensitive explosive. Blasting agents such as ANFO require a booster to achieve detonation. A booster can be a more energetic charge placed in a specific location in a blasthole to have more energy in a harder rock layer.

A Delay is the time interval between successive detonations. These are used by the blaster to provide a progressive relief for rock to displace into as the shot evolves.

Detonating Cord is a round, high detonation velocity, flexible cord containing a center core of high explosive, usually PETN, within a reinforced waterproofing covering.

A Detonator is a device, either electric or non-electric, that is inserted into an explosive and used to cause the detonation.

The Initiation System is the entire system used to initiate the blast. This includes the detonator (electric or non-electric), delay devices, and all their connecting parts.

Introduction to Types of Rock Blasting.

Conventional blasting techniques include several different types of blasting that are commonly used:

Production Blasting is a blast that is intended to fragment and displace a designed volume of rock. The focus of this blast is the maximum volume of rock fragmented per amount of explosive used. This blasting technique by itself will produce a ragged rock face and does not provide protection against back break or overbreak at the new rock face.

Secondary Blasting is a secondary blast used to fragment rock that was not adequately fragmented by the initial production blast.

Presplit Blasting is a controlled blasting procedure that is used to produce a shear plane within the rock mass. Most often used to produce a clean, relatively solid rock cut face, presplit blasting involves the use of boreholes that are more closely spaced and lightly loaded than pro- duction blastholes. A crack propagates along this line of more lightly loaded holes that are detonated ahead of the main production blast. The crack is intended to protect the new rock cut face, or some other perimeter, by allowing the blasting gases to escape and for blasting cracks to terminate at the presplit creak. This has the effect of reducing backbreak, or overbreak in the new rock wall, thus preserving its structural integrity. This method is used extensively for roadway rock cuts, lock walls, and any other cuts to produce a solid wall with little or no backbreak is needed. It is used to reduce the amount of rockfall that can occur from the exposed face than could be expected using production blasting alone. When well executed, the exposed rock face may contain "half casts" of the boreholes used for blasting. Presplit blastholes are fired before the production blast, which is between the presplit blast and the free face. The production blast may follow the presplit blast with a connected delay or fire completely separate from each other. During the initial evaluation period of pre-splitting results, it is recommended that the presplit blast be its own blast that way the results can be evaluated.

Precision Presplit Blasting is a controlled blasting procedure that is used to produce a shear plane within a weak rock or one that is geologically complicated with the minimum amount of explosive and minimum overbreak. Used to produce a clean, relatively solid rock cut face where rock is weak, or rock has extensive geologic discontinuities such as closely spaced jointing. Precision presplit blasting involves the use of boreholes that are more closely spaced and loaded lighter than standard Presplit blastholes. A crack propagates along this line of more lightly loaded holes that are detonated ahead of the main production blast. The crack is intended to protect the new rock cut face, or some other perimeter. When well executed, the exposed rock face may contain "half casts" of the boreholes used for blasting. Precision Presplit blastholes are fired before the production blast, which is between the presplit blast and the free face.

Smooth Blasting, commonly called "Trim Blasting" is similar to presplit blasting, but the holes are detonated after the production blastholes are detonated. The purpose is to blast loose remaining burden with lighter charges while not causing any additional damage to the new rock wall face. Smooth blasting is commonly used underground.

Precision Trim Blasting is a controlled blasting procedure that is used to produce a shear plane within a weak rock or one that is geologically complicated with the minimum amount of explosive and minimum overbreak. It is used to produce a clean, relatively solid rock cut face where rock is weak, or rock has extensive geologic discontinuities such as closely spaced jointing. Precision trim blasting involves the use of boreholes that are more closely spaced and loaded lighter than standard Trim blastholes. Precision Trim blastholes are fired after the pro- duction blast, which is between the perimeter and the free face.

Buffer Blasting refers to a designated section of rock between a slope or wall to be formed by line drilling or presplitting during excavation and the production blast. The explosives in the buffer blasthole and the burden in the buffer zone are reduced to prevent damage to the final rock slopes or face. Buffer blasting can be fired after the adjacent production blast or as a separate shot.

Sinking Cut Blast is where a blast has only the top or horizontal face and has no vertical or sloped free face (Figure 6). Rock cannot be displaced sideways in this type of blasting and thus it must be expelled upwards. Flyrock is a particular problem with this type of blast as it is not possible to direct the blasting energy in any direction but up. This must be accounted for during design and monitoring.

Figure 6. Sinking Shot Loaded and Hooked up for Excavating a Lock Monolith Foundation.

Features of Rock Blasting and Control.

Flyrock is the rock that is launched into the air and travels further than was intended by the blast design. Flyrock can cause considerable damage.

Blasting Mats are used to help control flyrock (Figures 7 and 8). These are very heavy mats usually made from rubber tires, conveyor belts, steel cables, or other similar materials. Blasting mats are of particular use where flyrock may damage buildings or other structures.

Heave (also called Throw) is the distance the rock displaces from the in-situ condition due to blasting.

Powder Factor is the ratio between the weight of explosives that have been detonated and the total volume of rock that was blasted. For construction practice, this volume is measures in cubic yards or cubic meters. The powder factor of the blast includes the total weight of explosives and the total volume of rock above grade level. The powder factor should always be re- ported on construction monitoring documents. The units of powder factor are pounds per cubic yard or kilograms per cubic meter.

Figure 7. Rubber Blasting Mats Being Lowered onto Shot at Kentucky Lock.

Figure 8. Wire Blasting Mats Protects Structures

Explosives

In excavation, explosives are used as a tool to provide the energy needed to fragment and displace the rock. This energy is provided by a rapid chemical reaction in the ex- plosive induced by shock, impact, or heat. Modern explosives used for construction purposes require an initiation system of some kind, a shock, impact, or heat to start the chemical reaction needed to produce the work required. This section discusses the types and characteristics of ex- plosives as well as initiation systems used in rock excavation. It begins with some theory on the mechanics of rock breakage to give the reader an introduction to how explosives work and ends with a discussion of some safety and transportation issues surrounding the use of explosives.

Mechanics of Rock Breakage.

There are four basic effects of the detonation of explosives used for rock excavation: (1) rock fragmentation, (2) rock displacement, (3) ground vibration and (4) air overpressure. These effects are controlled by the confinement of the explosive and also the two basic forms of energy that are released when high explosives detonate: (1) shock energy and (2) gas energy. Explosives can be detonated in an unconfined or confined manner. An example of a confined application is when explosives are used in a borehole with stemming material and surrounded by rock.

Although both types of energy are released during the detonation process, the blaster can select explosives with different proportions of shock or gas energy to suit a particular application. If explosives are used in an unconfined manner, such as mud capping boulders or for shearing structural members in demolition, the selection of an explosive with high shock energy is advantageous. On the other hand, if explosives are used in boreholes and confined by the use of stemming materials, an explosive with a high gas energy output is beneficial.

To help form a mental picture of the difference between the two types of energy, com- pare the difference in reaction of a low and high explosives. Low explosives, such as black pow- der, are those that deflagrate, or burn, very rapidly. These explosives may have reaction velocities of 2000 to 5000 ft. per second and produce no shock energy. They produce work only from gas expansion. High explosives, such as dynamite, detonate and produce not only gas pressure, but also shock pressure.

Figure 9 shows these differences with a diagram of reacting cartridges of low explosive and a high explosive. For a low explosive, if the reaction is stopped when the cartridge has been partially consumed and the pressure profile is examined, one can see a steady rise in pressure due to the reaction until the maximum pressure is reached. Low explosives produce only gas pressure during the combustion process. A high explosive detonates and exhibits a different pressure profile producing shock energy at the reaction front followed by the gas pressure.

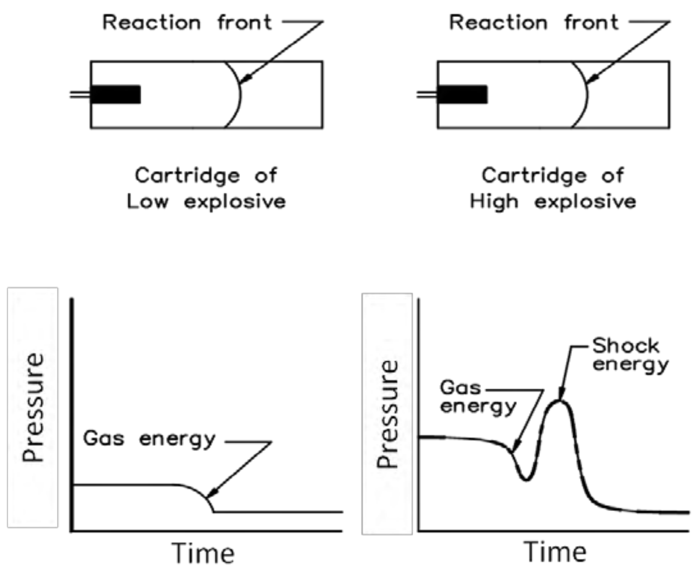

Figure 9. Pressure Profiles for Low (Left) and High (Right) Explosives.

This shock energy produced by the high explosive normally results in a higher pressure than gas expansion produces. After the shock energy passes, gas energy is released. The gas energy in high explosives is much greater than the gas energy released in low explosives. The shock pressure is a transient pressure that travels at the explosives rate of detonation. This pressure is estimated to account for only 10% to 15% of the total available useful work energy in the explosion. The gas pressure accounts for 85% to 90% of the useful work energy and follows the shock energy. However, unlike the transient shock energy, the gas energy produces a force that is constantly maintained until the confining vessel, usually the borehole, ruptures. This causes fracturing in the rock that is continued until this pressure is relieved. In an ideal model, a homogeneous rock mass, the shock energy will propagate outward, out running the growing fracture tips at the edges of the rupture, much like the ripples on a pond. This energy will attenuate proportional to the square of the distance from the blast and in relation to the elastic properties of the rock. While this picture is more complicated when taken from the ideal of homogeneous rock and applied in a rock mass where the reaction will be modified by the presence of inhomogeneities and discontinuities it is useful to understand how this energy will move through and idealized rock before adding the complicating factors of more site specific rock mass.

The shock energy is commonly believed to result from the detonation pressure of the ex- plosion. The detonation pressure, a form of kinetic energy, is a function of the explosive density times the explosion detonation velocity squared. Determination of the detonation pressure is very complex, but an estimate of the detonation pressure can be calculated with:

$$P = \frac{4.18 \times 10^{-7} \times Ve^2 SG_e}{1 + 0.8 SG_e}$$

P = Detonation pressure (Kilobar, 1 Kilobar = 14,504 psi).

SG_e = *Specific Gravity of the explosive.*

Ve^2 = *detonation velocity (ft/s).*

The detonation pressure or shock energy can be considered similar to kinetic energy; it is at its maximum in the direction of travel. This means the detonation pressure will be highest in the end of the explosive cartridge opposite where the initiation occurs. This property explains why when mudcapping boulders, it is more effective to place the cartridge with the bottom directed toward the boulder, rather than placed sideways on the boulder (Figure 10). Therefore, to maximize the use of the detonation pressure, the explosive should be in good contact with the rock to be blasted. An explosive with high density and high detonation velocity will result in a high detonation pressure.

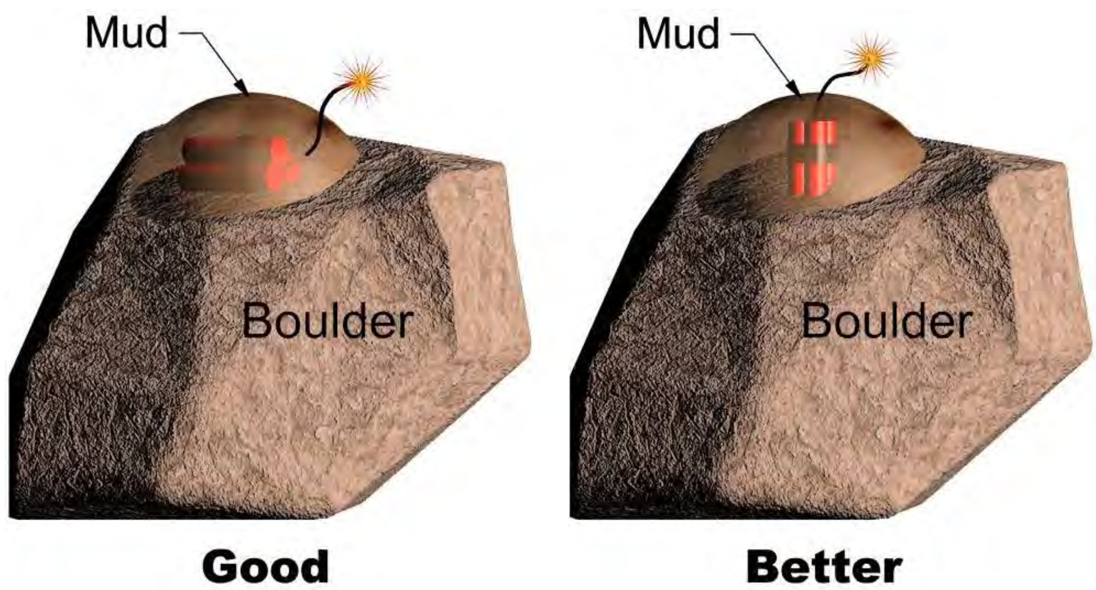

Figure 10. Mudcapping Explosive Placement.

The gas energy released during the detonation process causes the majority of rock breakage in rock blasting where charges are confined in boreholes. The gas pressure, often called explosion pressure, is the pressure that is exerted on the borehole walls by the expanding gases after the chemical reaction has been completed.

Explosion pressure results from the amount of gases liberated per unit weight of explosive and the amount of heat liberated during the reaction. The higher the temperature produced, the higher the gas pressure. If more gas volume is liberated at the same temperature, the pressure will also increase. For a quick approximation, it is often assumed that explosion pressure is ap- proximately one-half of the detonation pressure. The nomograph pictured in Figure 11 shows explosive density, explosion pressure, detonation pressure, and detonation velocity.

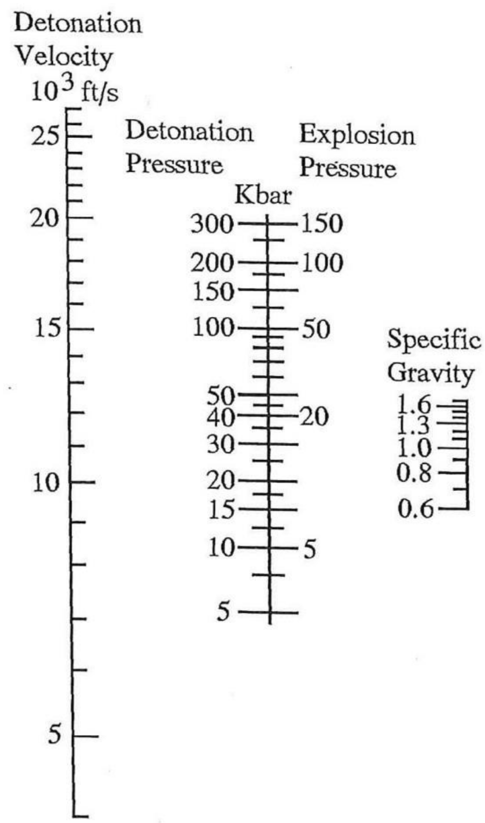

Figure 11. Nomograph of Detonation and Explosion Pressures.

Confinement of the charge also has a significant effect on the amount of energy that is directed toward the rock fragmentation as opposed to air overpressure or air blast. Figure 10 demonstrates, with the older mechanism of mudcapping, that the mud placed on top of an unconfined explosive charge in either configuration provides almost no confinement for an explosive. Unconfined charges placed on boulders and subsequently detonated produce shock energy that will be transmitted into the boulder at the point of contact between the charge and the boulder. Since most of the charge is not in contact with the boulder, the majority of the useful explosive energy travels out into space and is wasted. This wasted energy manifests itself in excessive air blast overpressure. Gas pressure can never build since the charge is essentially unconfined; therefore, gas energy does little work. The mud does couple the explosive to the rock and acts as a wave trap that reflects some of the escaping shock energy downward toward the boulder (Figure 12). Ultimately, if a borehole charge was used instead of placing the charge on top of the boulder considerably less explosive can be used as it will harness both the shock and the gas energy.

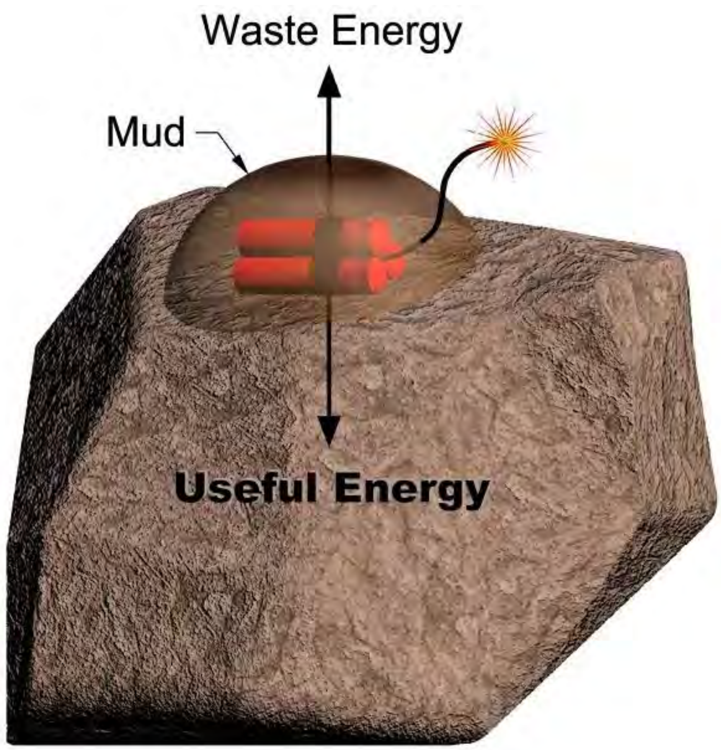

Figure 12. Reflection of Energy into the Boulder from the Older Method for Mudcapping Cartridge Placement.

Confined charges have four basic mechanisms that contribute to rock breakage: (1) shock wave, which can initiate microfractures on the borehole wall and moves through the rock uniformly in all directions around the charge causing initial radial microfractures, (2) sustained gas pressure, which penetrates and extends the radial microfractures toward the face, (3) the face begins to bend outward due to the expanding gases, and (4) fractures are created in the third dimension as a result of this flexural failure or bending.

The first occurrence in time, but the least significant mechanism of breakage, is caused by the shock wave or stress wave. At most, the shock wave causes radial microfractures to form on the borehole walls and may initiate microfractures at major discontinuities in the burden. This transient pressure pulse quickly diminishes with distance from the borehole. Since the propagation velocity of the pulse is approximately 2.5 to 5 times the maximum crack propagation velocity, the pulse quickly outruns the crack propagation or fracture propagation.

The more important mechanism is the sustained gas pressure. When the solid explosive is transformed into a gas during the detonation process, the borehole acts similar to a cylindrical pressure vessel. Failures in pressure vessels, such as water pipes or hydraulic lines, offer an analogy to this mechanism of rock breakage. When the vessel is over pressurized, the pressure exerted perpendicular to the confining vessel's walls will cause a fracture to occur at the weakest point. In the case of frozen water pipes, a longitudinal split occurs parallel to the axis of the pipe (Figure 13).The major difference between pressurizing a borehole and pressurizing a water pipe is rate of loading. A borehole is over pressurized almost instantaneously and there- fore does not fail at one weakest point along the borehole wall. Instead, it will simultaneously fail in many locations in a geometric pattern. Each resulting fracture will be oriented parallel to the axis of the borehole. Failure by this mechanism has been recognized for many years and is commonly called radial cracking. Figure 14 shows this same radial fracturing in rock at the bot- tom of a borehole after rock has been removed.

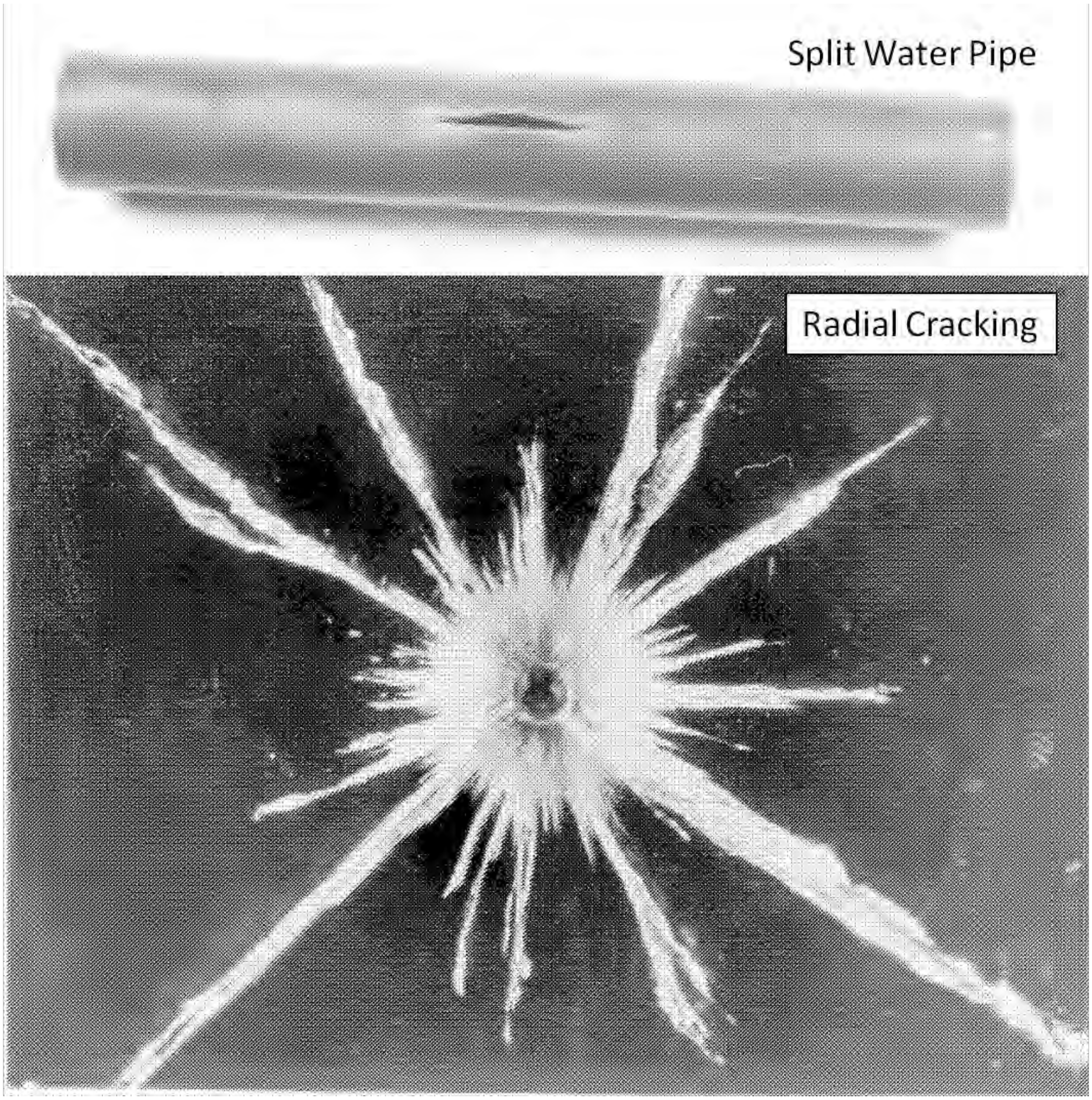

Figure 13. Split Water Pipe Due to Overpressure and Radial Cracking Around a Hole in Plexiglas.

Figure 14. Radial Fracturing in the Subdrill Due to Blasting.

The third mechanism is relief of the sustained gas pressure by the free face and movement of the cracked rock mass. There is a time lag in the rock mass from the formation of the initial radial cracking and the extension of that radial cracking toward the relief face. The distance of that face influences the formation of the radial crack system. Here the burden in the rock is transformed from a solid rock mass into one that is broken by the radial cracks in many wedge-shaped or pie-shaped pieces. These wedges function as columns, supporting the burden weight. Columns become weaker if their length-to-diameter ratio or slenderness ratio increases. Therefore, once the massive burden is transformed into pie-shaped pieces with a fixed bench height, it has been severely weakened due to the fact that its slenderness ratio has increased.

The high-pressure gases subject the wedges to forces acting perpendicular to the axis of the hole that push toward relief or toward the line of least resistance.

This concept of relief perpendicular to the axis of the hole has been known for well over a hundred years. Relief must be available perpendicular to the axis of the hole for borehole charges to function properly. If relief is not available, only radial cracks will form. As a result, boreholes will crater, or the stemming will be blown out. In either case, the fragmentation suffers and environmental problems result. The direction and extent of the radial cracking system is controlled by the selection of proper burden from the borehole to the face (Figure 15).

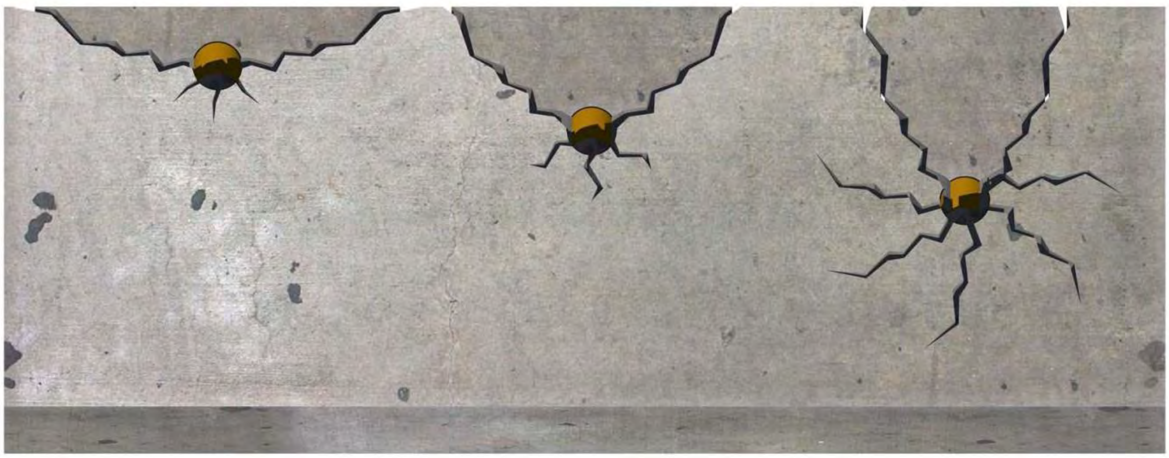

Figure 15. Influence of Distance to the Relief Face on Development of Radial Cracks.

Finally, the flexure of the entire mass ensures cracking in the third dimension so that the rock is displaced outward from the face. This is the second major breakage mechanism called "flexural failure." In most blasting operations, the first visible movement occurs when the face bows outward near the center (Figure 2-8a). In other words, the center portion of the face is moving faster than the top or bottom of the burden. This type of bowing or bending action does not always occur. One can find cases where instead of the center bowing outward, the top or bottom portion of the burden is cantilevering outward. These other two cases cause problems in blasting. The blast design controls the mechanism of "flexural failure." Figure 16 shows the three mechanisms often seen in rock blasting.

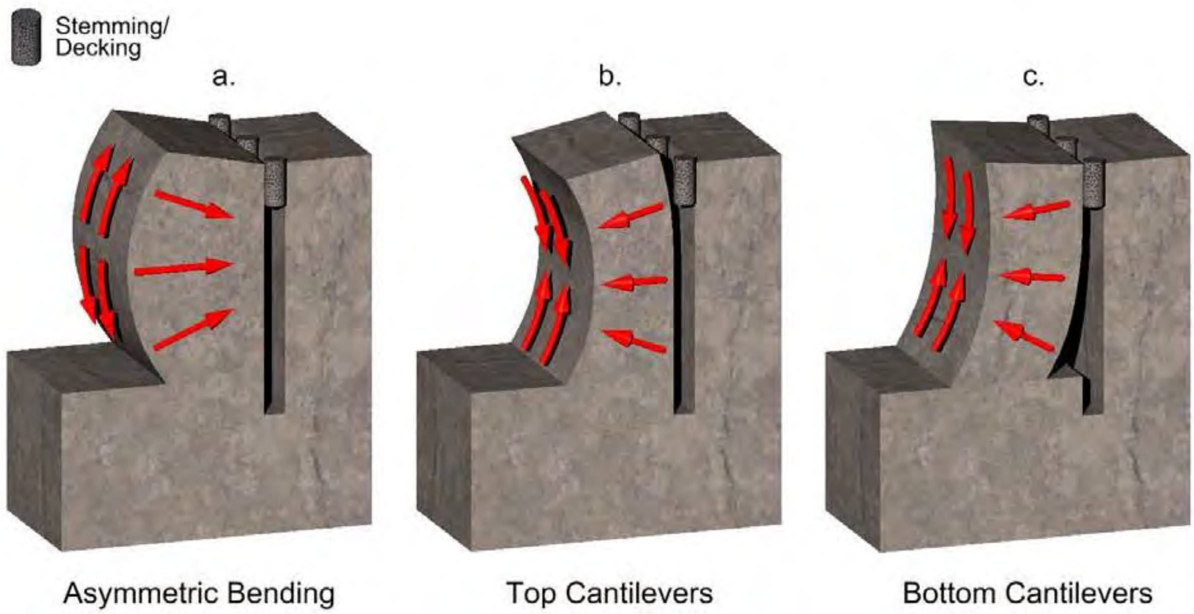

Figure 16. Flexure and Direction of Displacement of the Rock Mass.

Two general modes of flexural failure of the burden exist. In one case, the burden bends outward or bulges in the center more quickly than it does on the top or bottom (Figure 16a). When the burden rock bulges at its center, tensile stresses result at the face and compression results near the charge. Under this type of bending condition, the rock will break from the face back toward the hole. This mode of failure generally leads to desirable breakage.

In the second case, the top or the bottom of the burden moves at a higher rate than the center (Figure 16 b,c) so the rock is cantilevered outward. The face is put into compression and the borehole walls are in tension. This mechanism occurs when cracks between blastholes link before the burden is broken; it is normally caused by insufficient blasthole spacing. When the cracks be- tween holes reach the surface, gases can be prematurely vented before they have accomplished all potential work. Air blast and flyrock can result along with potential bottom problems.

For all three cases, this breakage mechanism is called flexural rupture or flexural failure. The individual pie-shaped columns of rock caused by the radial cracking will also be influenced by a force perpendicular to the length of the column. This would be similar to beam loading conditions. When discussing beam loading, the stiffness ratio is significant. The stiffness ratio relates the thickness of the beam to its length. The effect of the stiffness can be explained by using, for example, a full-length pencil. It is quite easy to break a full-length pencil by grasping the pencil on either end. However, if the same force is exerted on a much shorter, for example 2 in long pencil, it becomes more difficult to break. The pencil's diameter has not changed; the only thing that has changed is its length. A similar stiffness phenomenon also occurs in blasting. The burden rock is more difficult to break by flexural failure when bench heights approach the bur- den dimension in length. When bench heights are many times the burden in length, the burden rock is more easily broken.

The bending mechanism or flexural failure is controlled by selecting the proper blasthole spacing and initiation time of adjacent holes. When blasthole timing results in charges being delayed from one another along a row of holes, the spacing must be less than that required if all the holes in a row were fired simultaneously. The selection of the proper spacing is further complicated by the stiffness ratio. As bench heights are reduced compared to the burden, one must also reduce the spacing between holes to overcome the problems of stiffness.

Types of Explosives.

The products used as the main borehole charge can be broken into three generic categories, dynamite, slurries, and blasting agents such as ANFO (Figure 17). A fourth, very minor, category will be added to the discussion, which is the binary (or two-component) explosives. Although the volume of binary explosives sold annually is insignificant when compared to the other major generic categories, its unique properties warrant its mention.

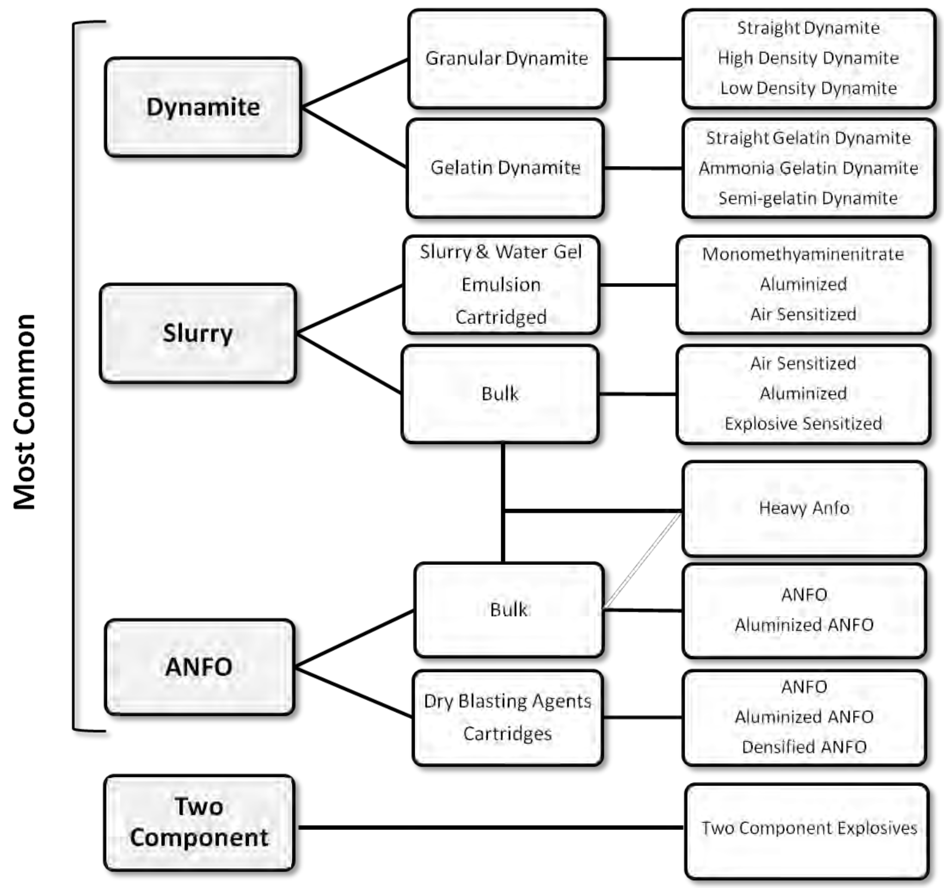

Figure 17. Types of Explosives Commonly Used for Rock Excavation.

The term "high explosive" most often refers to any product used in blasting that is cap sensitive and that reacts at a speed faster than the speed of sound in the explosive media. The reaction must be accompanied by a shock wave for it to be considered a high explosive. All the generic categories discussed in this section are high explosives from the standpoint that they will all detonate.

A blasting agent is a classification based on storage and transportation and is a sub-class of high explosive. Explosives that are blasting agents are less sensitive to initiation and therefore can be stored and transported under different regulations than what would normally be used for more sensitive high explosives. ANFO is most often called a blasting agent but does not detract from an explosive's ability to detonate or function as a high explosive.

Dynamite.

Most dynamites are nitroglycerin-based products. A few manufacturers of dynamite have products in which they substituted non-headache producing high explosives such as nitro-starch for the nitroglycerin. Dynamites are the most sensitive of all the generic classes of explosives. Because of their sensitivity, they offer an extra margin of dependability in the blasthole since gaps in loading within the explosive column and many other environmental factors that cause other explosives to misfire do notoccur as often with dynamite.

There are two major sub-classifications within the dynamite family: granular dynamite and gelatin dynamite (Figure 18). Granular dynamite is a compound that uses a single high explosive base such as nitroglycerin. Gelatin dynamite is a mixture of nitroglycerin and nitrocellulose that pro- duces a rubbery waterproof compound.

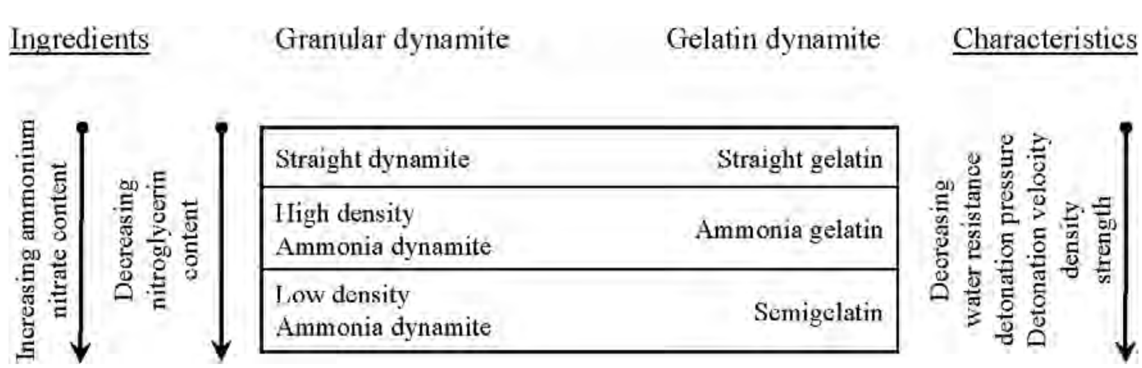

Figure 18. Classification of Dynamite.

Straight dynamite consists of nitroglycerin, sodium nitrate, carbonaceous fuels, sulfur, and antacids. The term “straight” means that the dynamite contains no AN. Straight dynamite is the most sensitive commercial high explosive in use today. It should not be used for most construction applications since its sensitivity to shock can result in sympathetic detonation from adjacent holes, firing on an earlier than planned delay. On the other hand, straight dynamite is an extremely valuable product for dirt ditching (excavation of a ditch in dirt using an explosive compound). The sympathetic detonation previously discussed is an attribute in dirt ditching because it eliminates the need for a detonator in each and every hole.

High density extra dynamite is the most widely used product. It is similar to straight dyna- mite except that some of the nitroglycerin and sodium nitrate is replaced with AN. The ammonia or extra dynamite is less sensitive to shock and friction than the straight dynamite. It has found broad use in all applications, quarries, underground mines, and construction.

Low density extra dynamites are similar in composition to the high-density products, except that more nitroglycerin and sodium nitrate is replaced with AN. Since the cartridge contains a large proportion of AN, its’ bulk or volume strength is relatively low. This product is useful in soft rock or where a deliberate attempt is made to limit the energy placed into the blasthole.

Straight gelatins are blasting gels with additional sodium nitrate, carbonaceous fuel, and sometimes sulfur. In strength, it is the gelatinous equivalent of straight dynamite. A straight blasting gelatin is the most powerful nitroglycerin-based explosive. A straight gel, because of its composition, is also the most waterproof dynamite.

Ammonia gelatin is sometimes called special or extra gelatin. It is a mixture of straight gelatin with additional AN added to replace some of the nitroglycerin and sodium nitrate. Ammonia gels are suitable for wet conditions and are primarily used as bottom loads in small diameter blastholes. Ammonia gelatins do not have the water resistance of a straight gel. Ammonia gels are often used as primers for blasting agents.

Semi gelatin dynamite is similar to ammonia dynamite except it normally contains additional AN. This product has moderate water resistance and is a low-cost water-resistant product commonly used by the construction industry.

Slurry Explosives.

A slurry explosive is a mixture of AN or other nitrates and a fuel sensitizer, which can either be a hydrocarbon, or hydrocarbons and aluminum. In some cases, explosive sensitizers, such as TNT or nitrocellulose are used, along with varying amounts of water (Figure 19). There are two general classes of water-based slurries; watergels and emulsions. An emulsion is somewhat different from a water gel slurry in characteristics, but the composition contains similar ingredients and functions similarly in the blasthole. In general, emulsions have a somewhat higher detonation velocity and, in some cases, may tend to be wet or adhere to the blasthole causing difficulties in bulk loading. For discussion purposes, emulsions, and water gels will be treated under the generic family of slurries.

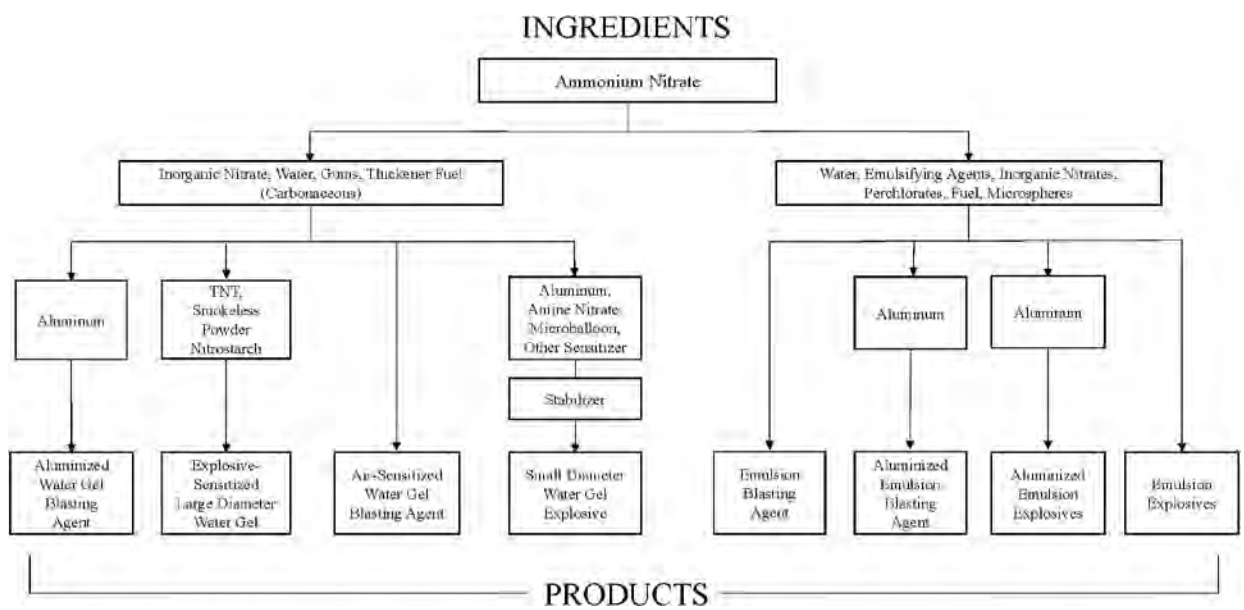

Figure 19. Classification and Types of Slurries.

Cartridge slurries come in both large and small diameters. In general, cartridges less than2 in. in diameter are made cap sensitive so that they can be substituted for dynamite. The temperature sensitivity of watergel slurries and their lower sensitivity can cause problems when substituted for some dynamite applications. The blaster(s) must be aware of some of the limitations before trying a one-for-one substitution. The larger diameter cartridge slurries may not be cap sensitive and must be primed with cap sensitive explosives. In general, large diameter slurries are the least sensitive. Cartridge slurries are normally sensitized with monomethＯlamine nitrate or aluminum and are also air sensitized. Air sensitizing is accomplished by the addition of microspheres, chemical gassing, entrapping air, or gas during the mixing process itself.

Bulk slurries are sensitized by one of three methods: air sensitizing, addition of aluminum and addition of nitrocellulose or TNT. Air sensitizing can be accomplished by the addition of gas- sing agents, which after being pumped into the blasthole, produce small gas bubbles throughout the mixture. Slurries containing neither aluminum nor explosive sensitizers are the cheapest, however, they are often the least dense and the least powerful. In wet conditions where dewatering is not used or where it is not practical, low cost slurries offer competition to ANFO. Table 1, below, is a comparison of the properties ofwater gels and emulsions.

Table 1. Properties of Water Gels and Emulsions.

Property	Watergel	Emulsion
Highest Detonation Velocity		X
High Electrical Conductivity	X	
Contains High Explosive	X	
Problems in Cold Environments	X	
Hazardous to Manufacture	X	
Highest Cost	X	

It should be noted out that these slurries have less energy than ANFO on a by weight basis. Higher cost aluminized slurries and those containing significant amounts of other high explosive sensitizers produce significantly more energy because of their density and are used for blasting wet blastholes. An alternative to using high energy slurries is dewatering blastholes, where possible, with submersible blasthole pumps and using polyethylene blasthole liners within the hole with AN as the explosive. Another option is to use the cartridge ANFO products. In most applications, the use of pumping for water removal with sleeves and AN, or the use of cartridge ANFO products, will pro- duce blasting costs that are significantly less than would result from using higher priced slurries. These supplies are available from many explosive distributors (Figure 20).

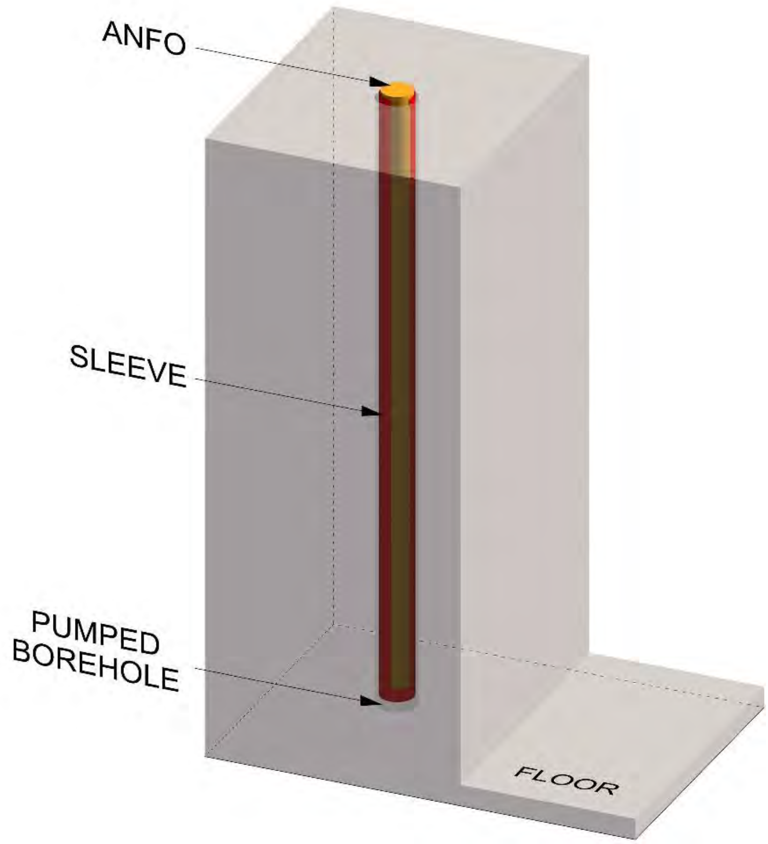

Figure 20. Pumped ANFO with Sleeve in Borehole.

ANFO and Dry Blasting Agents.

Dry blasting agents are the most common of all explosives used today. Approximately 80% of the explosives used in the United States are dry blasting agents. The term dry blasting agent describes any material in which no water is used in the formulation. Figure 21 shows the commonly used AN-based blasting agent formulations.

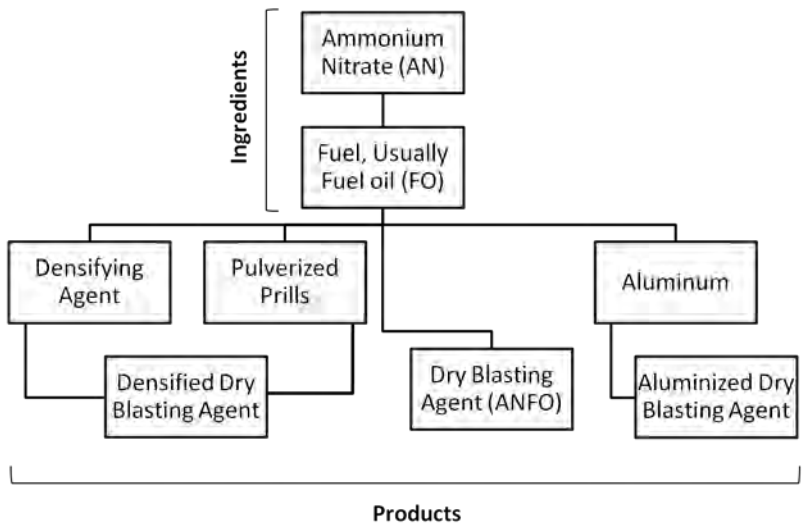

Figure 21. AN-Based Formulations.

Early dry blasting agents employed fuels of solid carbon or coal dust combined with AN in various forms. Through experimentation, it was found that solid fuels tend to segregate in transportation and provide less than optimum blasting results. It was found that diesel oil mixed with porous AN prills gave the best overall blasting results. The term ANFO has become synonymous with dry blasting agents. An oxygen balanced mixture of ANFO is the cheapest source of explosive energy available today. Adding finely divided aluminum to dry blasting agents increases the energy output, but also increases cost.

Bulk ANFO is prilled ammonium nitrate and fuel oil. The prills are spherical particles of AN manufactured in a prilling tower with a similar process to that used in making bird shot for shot- gun shells. AN prills are also used in the fertilizer industry although there are differences between the fertilizer grade and the blasting grade prills. The blasting prill is considered a porous prill, which better distributes the fuel oil and results in better blasting performance. Table 2 lists the difference in properties of fertilizer and blasting prill. Figure 22 shows ANFO prills alongside a typical set of car keys (for scale).

Table 2. Properties of Fertilizer and Blasting Prills (Atlas).

Property	Fertilizer Prill	Blasting Prill
Inert Coating	3-5%	0.5-1%
Hardness	Very Hard	Soft

Physical Form	Solid Crystal	Porous
Fuel Oil Distribution	Surface Only	Throughout Prill
Minimum diameter for unconfined detonation	9 in	2.5 in
4 in Confined Velocity	6,000 ft/s	11,000 ft/s

Figure 22. ANFO Prills.

The prills are often either blown or augured into the blasthole from a bulk truck. The pre- mixed ANFO can be placed in the truck for borehole loading, or the dry ammonium nitrate and diesel oil can be mixed in the field as the material is being placed in the borehole. The blasting industry has a great dependence on dry blasting agents because of the large volume used. Dry blasting agents will not function properly if placed in wet holes for extended periods of time. For this reason, the blaster should know the limitations the product.

AN, when bulk loaded into a blasthole, has no water resistance. If the product is placed in water and shot within a very short period of time, marginal detonation can occur with the production of rust colored fumes of nitrous oxide. The ammonium nitrate will dissolve in water and the ammonium nitrate will slump and often break initiator leads. The liberation of nitrous oxide is commonly seen on blasts involving bulk AN when operators have not taken the care to load the product in a proper manner, which ensures that it will stay dry.

When such a marginal detonation occurs, the product produces significantly less energy than it would be capable of producing under normal conditions. For this reason, blastholes geyser, flyrock is thrown, and other problems arise from using AN fuel oil mixtures in wet blastholes. If AN is placed in wet blastholes, it will absorb water. When the water content reaches approximately 9%, the AN may not detonate regardless of the size primer used. Figure 23 indicates the effect of water content on the performance of AN. As water content increases, minimum booster values also in- crease and detonation velocity decreases significantly.

For wet hole use, where blastholes are not pumped, an aluminized or densified ANFO cartridge can be used. Densified ANFO is made by: (1) crushing approximately 20% of the prills and adding them back into the normal prill mixture or, (2) adding iron compounds to increase the density of the cartridge. In both cases, the object is to produce an explosive with a density greater 1 so that it will sink in water.
Another type of ANFO cartridge is made from the normal bulk ANFO with a density of 0.8. This cartridge will not sink in water. However, it is advantageous to use this type of cartridged ANFO when placing in wet holes that were recently pumped and that contain only small amounts of water.

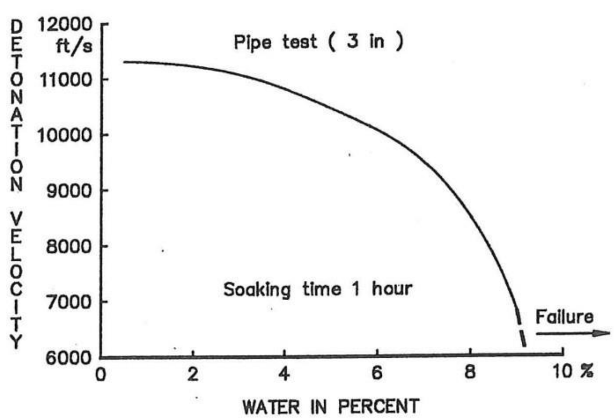

Figure 23. Effects of Water in ANFO on Detonation Velocity

Cartridge loading of explosives is more tedious and requires more personnel since the cartridges have to be physically taken to the blast site and stacked by each hole. The cartridges are then dropped into the borehole during the loading process. Heavy ANFO requires fewer personnel since the explosive is pumped directly into the blasthole from the bulk truck.

Heavy ANFO or ammonium nitrate blends are mixtures of ammonium nitrate prills, fuel oil, and slurries. The advantage to using heavy ANFO blends is that they can be mixed at the blasthole and quickly loaded into the hole (Figure 24). The ratio of the amount of slurry mixed with the ANFO can be changed to offer either a higher energy load or a load that is water resistant. The cost of heavy ANFO rises with increasing amounts of slurry. The advantage over cartridged products is that the entire blasthole is filled with energy and there is no wasted volume, such as would result from cartridge loading. A disadvantage with using the blends is that, since the explosive occupies the entire volume of the blasthole, any water in the hole is forced upward. This means that one may have to use the blend in the entire hole. Conversely with cartridge products, because of the annular space around the cartridge, one can build up to get out of water and then use the lower priced bulk ANFO.

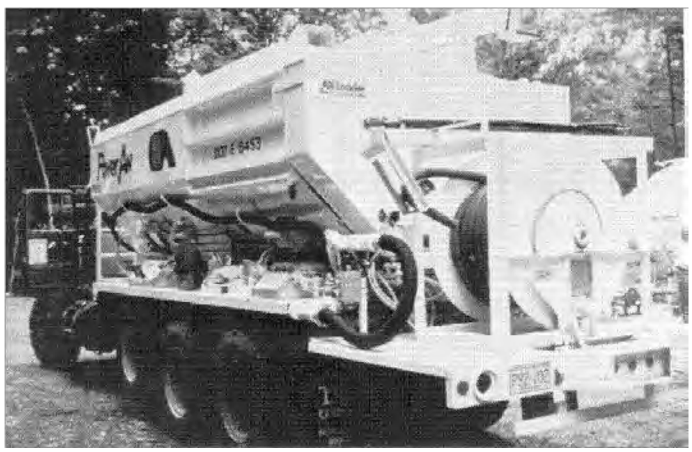

Figure 24. Heavy ANFO Bulk Loading Truck

Some operators try to use heavy ANFO in wet holes. However, they do not use mixtures that contain sufficient slurry. To provide the necessary water resistance, it is recommended that at least 50% slurry be used in heavy ANFO, which is to be used under wet borehole conditions.

Two-Component Explosives. Two-component explosives are often called “binary explosives” since they are made of two separate ingredients. Neither ingredient is explosive until mixed. Binary explosives are normally not classified as explosives. They can be shipped and stored as non-explosive materials. Commercially available, two-component explosives are a mixture of pulverized AN and nitromethane that have been dyed either red. These components are brought to the job site and only the amount needed are mixed. On mixing the material, it be- comes cap sensitive and is ready to use. These binary explosives can be used in applications where dynamite or cap sensitive slurries would otherwise be used. Binary explosives can also be used as primers for blasting agents and bulk slurries. In most states, binary explosives are not considered explosive until mixed. They, therefore, offer the small operator a greater degree of flexibility on the job. Their unit price is considerably higher than that of dynamite. However, the money saved in transportation and magazine costs outweighs the difference in unit price. If large quantities of explosives are needed on a particular job, the higher cost per weight and the inconvenience of onsite mixing negates any savings that would be realized from less stringent storage and transportation requirements.

Environmental Characteristics of Explosives.

The selection of the type of explosive to be used for a particular task is based on two primary criteria. The explosive must be able to function safely and reliably under the environmental conditions of the proposed use, and the explosive must be the most economical to use. Before any blaster selects an explosive to be used for a particular task, one must determine which explosives would best suit the particular environment and the performance characteristics that will suit the economy of the job. Five environmental characteristics are considered in the selection of explosives: (1) sensitiveness, (2) water resistance, (3) fumes, (4) flammability and (5) temperature resistance.

Sensitiveness (Critical Diameter)

Sensitiveness is the characteristic of an explosive that defines its ability to propagate through the entire length of the column charge and controls the minimum diameter for practical use. It can be expressed as the maximum separation distance (in centimeters) between a primed donor cartridge and an unprimed receptor cartridge, where detonation transfer will occur. It is measured by determining the explosive’s critical diameter. The term “critical diameter” is commonly used in the industry to define the minimum diameter in which a particular explosive compound will detonate reliably.

All explosive compounds have a critical diameter. For some explosive compounds, the critical diameter may be as little as a millimeter. On the other hand, another compound may have a critical diameter of 4 in. The diameter of the proposed borehole on a particular job will determine the maximum diameter of explosive column. This explosive diameter must be greater than the critical diameter of the explosive to be used in that borehole or it may not detonate. Good planning for a site is to allow for a somewhat larger borehole, often around an inch larger, than the critical diameter for the particular compound(s) to be used. Table 3 lists the critical diameter of some commonly used explosives.

Table 3. Sensitiveness (Critical Diameter) of Explosive Products.

	Critical Diameter		
Type	< 1 in	1 – 2 in	> 2 in
Granular Dynamite	X		
Gelatin Dynamite	X		
Cartridged Slurry*	X	X	X
Bulk Slurry*		X	X
Air Emplaced ANFO	X		
Poured ANFO		X	
Packaged ANFO*		X	X
Heavy ANFO			X

* Range due to different potential materials (see technical data sheets for particular material)

Water Resistance.

Water resistance is the ability of an explosive to withstand exposure to water without suffering detrimental effects in performance. Explosive products have two types of water resistance, internal and external. Internal water resistance is defined as water resistance provided by the explosive composition itself. For example, some emulsions and water gels can be pumped directly into boreholes filled with water. These explosives displace the water upward but are not penetrated by the water and show no detrimental effects if fired within a reasonable period of time. External water resistance is provided not by the explosive materials itself, but by the packaging or cartridging into which the material is placed. For example, ANFO has no internal water resistance yet, if it is placed in a sleeve or in a cartridge within a borehole, it can be kept dry and will perform satisfactorily. The sleeve on a cartridge provides the external water resistance for this particular product.

The effect that water has on explosives is that it can dissolve or leach some of the ingredients or cool the reaction to such a degree that the ideal products of detonation will not form even though the product is oxygen balanced. The emission of reddish-brown or yellow fumes from a blast often indicates inefficient detonation reactions frequently caused by water deterioration of the explosive. This condition can be remedied if a more water-resistant explosive or better external packaging is used.

Manufacturers can describe the water resistance of a product in two different ways. One way would be using terms such as excellent, good, fair, or poor (Table 4). When water is encountered in blasting operations, the explosive with at least a fair water resistance rating should be selected and this explosive should be detonated as soon as possible after loading. If the explosive is to be in water for an appreciable amount of time, it is advisable to select an explosive with at least a good water resistance rating. If water conditions are severe and the exposure time is significant, the prudent blaster may select an explosive with an excellent water resistance rating. Explosives with a poor water resistance rating should not be used in wet blastholes. Because of this, General USACE practice for blasting requires the use of packaged ANFO rather than bulk ANFO due to the likelihood on many USACE projects for encountering water in a borehole.

Table 4. Water Resistance of Commonly Used Explosives.

Type	Resistance
Granular Dynamite	Poor to good
Gelatin Dynamite	Good to excellent
Cartridged Slurry	Very good
Bulk Slurry	Very good
Air Emplaced ANFO	Poor
Poured ANFO	Poor
Packaged ANFO	Very good *
Heavy ANFO	Poor to very good
* Becomes poor if package is broken.	

Water resistance ratings have also been given numbers, such as a Class 1 water resistance would indicate 72 hours of exposure to water with no detrimental effects; Class 2 – 48 hours, Class 3 – 24 hours, and Class 4 – 12 hours. The descriptive method of rating water resistance is the one commonly seen on explosive data sheets. In general, product price is related to water resistance: the more water resistant the product, the higher the cost.

Water pressure tolerance is the ability to remain unaffected by high static. Some ex- plosive compounds are densified and desensitized by hydrostatic pressures, a condition, which results in deep boreholes. Combinations of factors such as cold weather and small primers will contribute to failure. Under these conditions, energy release may be minimal. Problems with water pressure tolerance most often occur with slurry and heavy ANFO.

Fumes

The fume class of an explosive is the measure of the amount of toxic gases produced in the detonation process. Carbon monoxide (CO) and oxides of nitrogen are the primary gases that are considered in the fume class ratings. Carbon monoxide is a colorless and odorless gas that in sufficient concentrations can displace oxygen in the blood, depriving organs and brain of re- quired oxygen. Although most commercial blasting agents are near oxygen balanced to minimize fumes and optimize energy release, fumes will occur, and the blaster should be aware of their production. In underground mining or construction applications, the problems that can result from producing fumes with inadequate ventilation is obvious and can be deadly. It should be pointed out that in surface operations, especially in deep cuts or trenches, fume production and retention can also be hazardous to the personnel on the job as ventilation may not be sufficient to displace CO generated by the blasting. Certain blasting conditions may also produce toxic fumes even when the explosive is oxygen balanced. Some conditions that can cause toxic fume production are insufficient charge diameter, inadequate water resistance, inadequate priming, and premature loss of confinement.

The Institute of Makers of Explosives (IME) have adopted a method of rating fumes. The test is conducted by the Bichel Gauge method. The volume of poisonous gases released per pounds of explosives is measured. If less than 276 in^3 of toxic fumes are produced per 0.44 pounds of explosives, the fume class rating would be 1. If 276 in^3 to 570 in^3 of poisonous gases are produced, the fume class rating is 2, and if 570 in^3 to 1,158 in^3 of poisonous gases are produced, the fume class rating is 3. Table 5 lists fume ratings of commonly used explosives.

Table 5. Fume Ratings of Commonly Used Explosives.

Type	Resistance
Granular Dynamite	Poor to good
Gelatin Dynamite	Fair to very good
Cartridged Slurry	Good to very good
Bulk Slurry	Fair to very good
Air Emplaced ANFO	Good *
Poured ANFO	Good *
Packaged ANFO	Good to very good
Heavy ANFO	Good*
*Can be poor under adverse conditions.	

Strictly speaking, carbon dioxide is not a fume since it is not a toxic gas by itself. However, many deaths have occurred over the years due to the generation of large amounts of carbon dioxide during blasting in confined areas. Although carbon dioxide is not poisonous, it is produced in large quantities in most blasts. In sufficient concentrations it has the effect of causing the involuntary muscles of the body to stop working. In other words, the heart and lungs would stop working if one was placed in high concentrations of carbon dioxide. If concentrations are 18% or higher in volume, death can occur by suffocation. An additional problem with carbon dioxide is that it has a density of 1.53 as compared to air and it would tend to pocket in low places in the excavation or where there is little movement of air. A simple solution to the problem is to use compressed air or ventilation fans to dilute any possible high concentrations in depressions of trenches.

A special note should be made here regarding ANFO and the fuel oil content on pro- duction of fumes at the site. Due to production methodology there can be some variability in the oil content in the ANFO prills. Particular attention should be paid to “red/orange fumes” where there is no water as this may indicate production of nitrous oxides. If carbon black appears on rocks after a blast or there are very dark grey gases, production of carbon monoxide may be suspected. CO content of the air can also be tested. Rowland and Mainiero in 2000 (Rowland and Mainiero, 2000) performed testing on types of fume productions depending on the oil content. Generally, where ANFO prills are too dry there will be increasing Nitrous Oxide fumes, where the prills are too wet, there is increasing Carbon Monoxide fumes. This can be an important safety consideration on a project. Testing can be performed to check the ANFO prill oil content. If other factors are well controlled, and there are still indications of a problem such as blasting gas color, or tests indicate excessive CO, ANFO product should be tested.

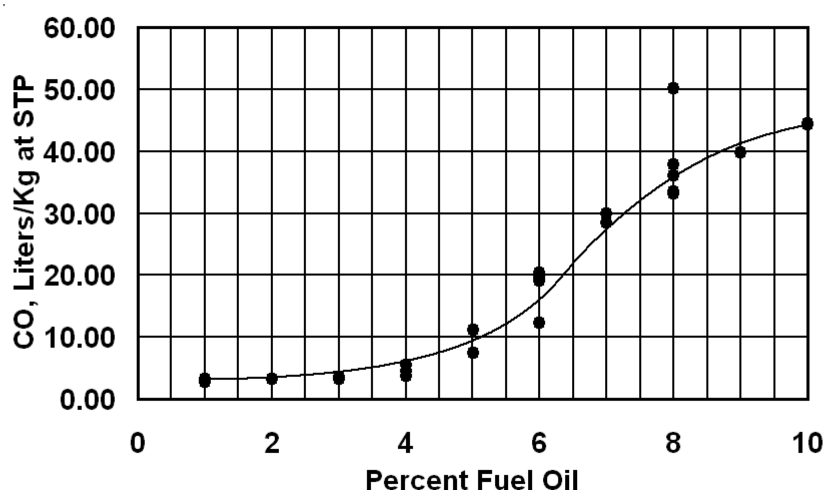

Figure 25. Effect of ANFO fuel oil content on carbon monoxide production (Rowland and Mainiero, 2000).

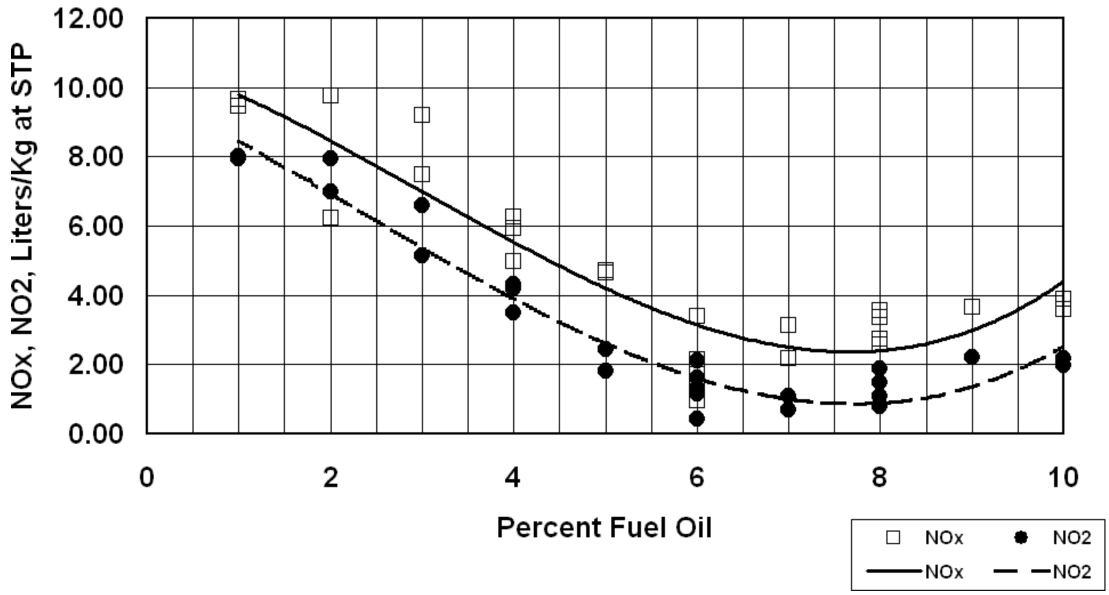

Figure 26. Effect of ANFO fuel oil content on nitrogen oxides and nitrogen dioxide production (Rowland and Mainiero, 2000).

Flammability

The flammability of an explosive is defined as the characteristic that deals with the ease of initiation from spark, fire, or flame. Some explosive compounds will explode from just a spark while others can be burned and will not detonate. Flammability is important from the standpoint of storage, transportation, and use. Some explosives, although very economical, have lost their marketability due to flammability. A good example is liquid oxygen and carbon, which was used in the 1950’s as a blasting agent. Its flammability and inherent safety problems caused its demise. Most explosive compounds used today are not anywhere near as flammable as liquid oxygen. However, accidents still occur due to flammability.

Over the past 2 decades, explosive products, in general, have become less flammable. Some manufacturers indicate that certain products can be burned without detonation in quantities as large as 44,093 pounds. This can lead to a false sense of security and the assumptions that all modern products today are relatively inflammable. This false sense of security has led to the death of people who have been careless with explosives. All explosive compounds should be treated as highly flammable and no smoking or open flames should be allowed.

Temperature Resistance.

Explosive compounds can suffer in performance if stored under extremely hot or cold conditions. Table 6 lists the temperature resistance of commonly used explosives. Under hot storage conditions, above 90°F, many compounds will slowly decompose or change properties; shelf life will be decreased. Storage of AN blasting agents in temperatures above 90°F can result in cycling, which will affect the performance and safety of the product.

Table 6. Temperature Resistance of Commonly Used Explosives.

Type	Resistance between 0 and 100°F
Granular Dynamite	Good
Gelatin Dynamite	Good
Cartridged Slurry	Poor below 40 F
Bulk Slurry	Poor below 40 F
Air Emplaced ANFO	Poor above 90 F
Poured ANFO	Poor above 90 F
Packaged ANFO	Poor above 90 F
Heavy ANFO	Poor below 40 F

The chemical formula for AN is NH_4NO_3. For its weight, it supplies more gas volume on detonation than any other explosive. In pure form, AN is almost inert and is composed of 60% oxygen by weight, 33% nitrogen, and 7% hydrogen. With the addition of fuel oil, the ideal oxygen balanced reactions for NH_4NO_3 is:

$$3N_2H_2O_3 + CH_2 \rightarrow 3N_2 + 7H_2 + COO_2$$

Two characteristics make this compound both unpredictable and dangerous. AN is water soluble and, if uncoated, can attract water from the atmosphere and slowly dissolve itself.

For this reason, the spherical particles, called prills, have a thin protective coating of silica flour (SiO_2), which offers some amount of water resistance. The second and most important characteristic is a phenomenon called cycling. Cycling is the ability of a material to change its crystal form with temperature. AN will have one of the five crystal forms depending on temperature:

- Above 257°F, cubic crystals exist.
- Above 184°F and below 257°F, tetragonal crystals exist.
- Above 90°F and below 184°F, orthorhombic crystals exist.
- Above 0°F and below 90°F, pseudo tetragonal crystals exist.
- Below 0°F, tetragonal crystals exist.

The cycling phenomena can seriously affect both the storage and performance of any explosive that contains AN. Most dynamites, both regular nitroglycerine (NG) or permissibles, contain some percentages of AN while blasting agents are composed almost totally of this com- pound. The two temperatures at which cycling will occur under normal conditions are 0 and 90°F. Therefore, any products that are stored over the winter or for a period of time during the summer most likely will undergo some amount of cycling. During the summer in a poorly ventilated powder magazine or storage bin located in the sun, the cycling temperature may be reached daily. The effect of cycling on AN when isolated from the humidity in the air is that the prills break down into finer and finer particles.

The prills are made up of pseudo tetragonal crystals. When the temperature exceeds 90°F, each crystal breaks into smaller crystals of orthorhombic structure. When the temperature again falls below 90 F, the small crystals break into even finer crystals of the pseudo tetragonal form. This process can continue until the density is no longer near 50 lb/ft^3, but can reach a density near 75 lb/ft^3. The density increase can make the product more sensitive and contain more energy per unit volume.

To further complicate the situation, some cartridged blasting agents or those stored in bins may not efficiently exclude humidity. After the AN has undergone cycling, the thin water-resistant coating (silica flour) is broken and the water vapor in the air condenses on the particles. As cycling continues water collects on the particles and the mass starts to dissolve. Recrystallizing into large crystals can occur with a reduction of temperature. Therefore, it is evident that a volume of AN after cycling may have very dense areas with decomposed prills and areas of large crystals. The performance of this product may range from that of a very powerful explosive to one that deflagrates or even one that will not shoot at all. Figure 27 shows the effect of this temperature cycling. Compare this to Figure

22, which shows intact prills.

Figure 27. AN Prills after Temperature Cycling

Extreme cold conditions can also affect the performance of products. Most dynamites and blasting agents will not freeze under ordinary exposure under the lowest temperature encountered in the United States. This is because the manufacturers have added ingredients to these products that allow them to perform properly in spite of the cold weather. Some products may tend to stiffen and become firm after prolonged exposure to low temperatures and may be- come more difficult to use in the field.

Slurry explosives, which include water gel and emulsions, can have serious detonation problems if stored in cold temperatures and not allowed to warm up before they are detonated. Slurries are quite different from the other products previously mentioned, such as dynamite and blasting agents. The problem comes about because in the past the blaster has been accustomed to using blasting agents from any manufacturer without having any problems due to cold weather. The blaster also has become accustomed to using dynamites from any manufacturer with good results. Today the slurry explosives do not all perform identically. Some can be used immediately if stored at temperatures of 0 °F where others will not detonate if stored at temperatures below 40°F.

The sensitivity of the product can become affected. The priming procedure, which was employed when the produce was stored at 68°F, may cause a misfire if the product is stored at 43°F. It is a good practice to consult the manufacturer's data sheet whenever any new product is introduced on the job, but it is absolutely essential to consult that data sheet if any new slurry explosives are introduced, since their properties and performance with temperatures can vary greatly.

Performance Characteristics of Explosives.

In the explosive selection process, the environ- mental conditions at the site can eliminate certain types of explosives from consideration. After the environmental conditions have been considered, one must consider the performance characteristics of explosives. Characteristics of main concern are: (1) sensitivity, (2) velocity, (3) density, (4) strength, and (5) cohesiveness.

a. Sensitivity. The sensitivity of an explosive product is defined by the amount of input energy necessary to cause the product to detonate reliably. This is sometimes called the minimum booster rating or minimum priming requirements. Some explosives require little energy to detonate reliably. The standard No. 8 blasting cap will detonate in dynamite and some of the cap sensitive slurry explosives. On the other hand, a blasting cap alone will not initiate bulk loaded ANFO and slurry that has not been altered by water. Cycled ANFO can be more sensitive than unaltered ANFO. For reliable detonation, one would have to use a booster or primer in conjunction with the blasting cap. Hazard sensitivity defines an explosive's response to the accidental addition of energy, such as bullet impact. Table 2-7 lists the sensitivity of commonly used explosives.

b. Velocity.

(1) The detonation velocity is the speed at which the reaction moves through the column of ex- plosive. It ranges from 5,000 ft/s to 25,000 ft/s for commercially used products. Detonation velocity is an important consideration for applications outside a borehole, such as plaster shooting, mud capping or shearing structural members. Detonation velocity has significantly less importance if the explosives are used in the borehole. Table 8 lists the detonation velocities of commonly used explosives.

Table 7. Sensitivity of Commonly Used Explosives.

Type	Hazard Sensitivity	Performance Sensitivity
Granular Dynamite	Moderate to high	Excellent
Gelatin Dynamite	Moderate	Excellent
Cartridged Slurry	Low	Good to very good
Bulk Slurry	Low	Good to very good

Air Emplaced ANFO	Low	Poor to good *
Poured ANFO	Low	Poor to good *
Packaged ANFO	Low	Good to very good
Heavy ANFO	Low	Poor to good*
* Heavily dependent on field conditions.		

Table 8. Detonation Velocities of Commonly used Explosives.

Type	Diameter		
	1.25 in	3 in	9 in
Granular Dynamite	7,000 – 19,000 ft/s		
Gelatin Dynamite	12,000 – 25,000 ft/s		
Cartridged Slurry	13,000 – 15,000 ft/s	14,000 – 16,000 ft/s	
Bulk Slurry		14,000 – 16,000 ft/s	12,000 – 19,000 ft/s
Air Emplaced ANFO	7,000 – 9,800 ft/s	12,000 – 13,000 ft/s	14,000 – 15,000 ft/s
Poured ANFO	6,000 – 7,000 ft/s	10,000 – 11,000 ft/s	14,000 – 15,000 ft/s
Packaged ANFO		10,000 – 12,000 ft/s	14,000 – 15,000 ft/s
Heavy ANFO			11,000 – 19,000 ft/s

(2) The detonation pressure is the near instantaneous pressure derived from the shock wave moving through the explosive compound. Table 2-9 lists detonation pressures of commonly used ex- plosives. When initiating one explosive with another, the shock pressure from the primary explosive is used to cause initiation in the secondary explosive. Detonation pressure can be related to borehole pressure, but it is not necessarily a linear relationship. Two explosives with similar detonation pressures will not necessarily have equal borehole pressure or gas pressure. Detonation pressure is calculated mathematically and reported as kilobars.

Table 9. Detonation Pressures of Commonly Used Explosives.

Type	Detonation Pressure (kbar)
Granular Dynamite	20 - 70
Gelatin Dynamite	70 -140

Cartridged Slurry	20 - 100
Bulk Slurry	20 - 100
Air Emplaced ANFO	7 - 45
Poured ANFO	7 - 45
Packaged ANFO	20 - 60
Heavy ANFO	20 - 90

(3) The detonation pressure is related to the density of the explosive and the reaction velocity. When selecting explosives for primers, detonation pressure is an important consideration.

c. Density.

(1) The density of an explosive is important because explosives are purchased, stored, and used on a weight basis. Density is normally expressed in terms of specific gravity, which is the ratio of explosive density to water density. The density of an explosive determines the weight of explosive that can be loaded into a specific borehole diameter. On a weight basis, there is not a great deal of difference in energy between various explosives. The difference in energy on a unit weight basis is nowhere near as great as the difference in energy on a volume basis. When hard rock is encountered and drilling is expensive, a denser product of higher cost is often justified. Table 10 lists the density of commonly used explosives.

Table 10. Density of Commonly Used Explosives.

Type	Density (Specific gravity)
Granular Dynamite	0.8 – 1.4
Gelatin Dynamite	1.0 – 1.7
Cartridged Slurry	1.1 – 1.3
Bulk Slurry	1.1 – 1.6
Air Emplaced ANFO	0.8 – 1.0
Poured ANFO	0.3 – 0.9
Packaged ANFO	1.1 – 1.2

Heavy ANFO	1.1 – 1.4

(2) The density of the explosive is commonly used as a tool to approximate strength and de- sign parameters between explosives of different manufacturers and different generic families. In general terms, products with higher explosive density are more energetic. A useful expression of density is what is commonly called “loading density” or the weight of explosive per length of charge at specified diameter. Loading density is used to determine the total kilograms of explosive that will be used per borehole and per blast. The density of commercial products range from about 0.3 to 1.6 g/cm³.

(3) An easy method to calculate loading density is:

$$d_e = 0.34 \text{ x } SG_e \text{ x } D_e^2$$

where:

de = Loading density (lbs/ft).

SGe = Specific gravity of the explosive (g/cm^3).

De = Diameter of the explosive (in).

d. Strength.

(1) Strength refers to the energy content of an explosive, which in turn is the measure of the force it can develop and its ability to do work. Strength has been rated by various manufacturers, both on an equal weight and an equal volume basis, and is commonly called weight strength and cartridge or bulk strength. There is no standard method to measure strength universally used by the ex- plosives manufacturers. Instead many different strength measurement methods exist such as the ballistic mortar test, seismic execution values, strain pulse measurement, cratering, calculation of detonation pressures, calculation of borehole pressures, and determination of heat release. However, none of these methods can be used satisfactorily for blast design purposes. Strength ratings are mis- leading and do not accurately compare rock fragmentation effectiveness with explosive type. In general, one can say that strength ratings are only a tool used to identify the end results and associate them with a specific product.

(2) One type of strength rating, the underwater shock and bubble energy

test used to determine the shock energy and the expanding gas energy, is used by some for design purposes. The bubble energy tests produce reliable results that can be used for approximating blast design dimensions.

(3) In the United States, explosives are commonly rated by methods called relative weight strength and relative bulk strength. Relative weight strength refers to an arbitrary index that com- pares the strength of equal weights of the explosive being rated and the standard explosive, which is ANFO. Relative bulk strengths compare to relative strengths of equal volumes of explosives. An arbitrary scale is used to compare the weight of a fixed volume of the explosive being rated to a fixed volume of ANFO. Normally, these rating numbers are given as either decimal fractions, or by arbitrarily setting the weight of ANFO as 100 and comparing other explosives against ANFO. There- fore, their values would be either somewhat greater or less than 100.

e. Cohesiveness. Cohesiveness is defined as the ability of the explosive to maintain its original shape. There are times when explosive must maintain its original shape and others when it should flow freely. For example, when blasting in cracked or broken ground, one definitely wants to use an explosive that will not flow into the cracked area causing holes to be overloaded. Conversely, in other applications such as in bulk loading, explosives should flow freely and should not bridge the borehole nor form gaps in the explosive column.

Selection of Explosives.

The explosives used in blasting need to function safely and reliably under the environmental conditions of the proposed use, but ultimately the explosives selected need to meet the objectives and goals of the overall Master Blasting Plan.

The first and foremost goal is to break rock. However, some other objectives that may need to be considered are: (1) a specific fragment size, (2) future handling of rock, (3) minimum damage to remaining rock, (4) rock displacement, (5) diggability, (6) vibration, (7) air blast, and (8) cost. It is important to understand that each site is different and mayinvolve multiple stakeholders.

The Master Blasting Plan must be tailored to meet the site-specific goals and objectives as defined by these stakeholders and reflected in the plans and specifications.

In the explosive selection process, the objectives and goals of the Master Blasting Plan can eliminate certain types of explosives from consideration on a particular project. After the objectives and goals have been considered, one must consider the limitations of blast site factors. Limitations of main concern are: (1) blast site location, (2) geology, (3) project specifications, (4) available explosives, and (5) available drill types.

a. Blast Site. The blast site can limit the selection of the explosives for a Master Blasting Plan. Concerns such as allowable blast size, proximity to sensitive locations, water conditions, and topography of site will all have an impact on the selection of the explosives. If the blast site is located near urban areas or sensitive structures where excessive vibrations are not tolerated the blast size (amount of explosives) will have to be reduced. As discussed earlier water greatly impacts the selection of explosives. The topography of a site may limit equipment mobility and could limit the selection of explosives by, for example, not allowing an explosives pump truck on site.

b. Geology. Geology greatly impacts the selection of explosives for a Master Blasting Plan. One of the first things to consider is the hardness of the rock and its resistance to blasting. ANFO will most likely work well on limestone, but it may have difficulty achieving proper frag- mentation on a harder gneiss. Other geological considerations that may limit explosive selection are bedding planes, faults, joints, voids, and caverns.

c. Project Specifications. The project specifications will impact the selection of explosives for a Master Blasting Plan. Project specifications are usually developed by the primary stake- holder and can be very prescriptive. Prescriptive specifications can greatly limit the selection of explosives by specifying a particular type of explosive of minimum density of explosive. Performance-based specification such as fragmentation size and blast size will also have an impact on selection.

d. Available Explosives. The availability of explosives will impact the selection of explosives for a Master Blasting Plan. If a particular explosive is readily available, making it cheaper, it will most likely be used. Also, if a blasting contractor has an inventory of a particular type of explosive, it will probably be used. Certain explosives may not be available for use for the particular project. Always consult controlling regulations applicable at the site before final selection of explosive product. Special permits for some products may require additional time or cost and this must also be factored into the selection of an appropriate product.

e. Available Drill Types. The availability of drilling equipment will impact the selection of explosives for a Master Blasting Plan. If the available drill equipment for a particular site can only drill 3-in. blastholes, the selection of an explosive like some heavy ANFO would not be a good choice since some heavy ANFO has a critical diameter of over 3-in.

Initiation Systems.

The initiation system transfers the detonation signal from hole-to-hole at a precise time and the selection of an initiation system is critical for the success of a blast. The initiation system not only controls the sequencing of blastholes, but also affects the amount of vibration generated from a blast, the amount of fragmentation produced, as well as the backbreak and violence that will occur.

Although the cost of the system is an important consideration, it should always be a secondary consideration, especially if the most economical initiation system causes problems with back- break, excessive ground vibration, or fragmentation. Often these negative issues can be much more costly than the savings that might be realized with using the cheaper system. An initiation system should be chosen first to achieve the needed results in the blasting program and only after that on comparing costs.

Initiators can be broken down into two broad classifications: electric and non-electric. Electric initiators use an electric charge to initiate the detonation. Non-electric (NONEL) methods include the use of blasting caps, detonating cord, delay primers, shock tubes, and boosters.

Electric and Electronic Initiation Systems. There are several different types of electric and electronic initiation systems: (1) electric blasting caps without delay, (2) electric blasting caps with delay, (3) electronic delay systems, and (4) the sequential blasting machine.

Electric Blasting Caps with delay

The electric blasting cap (EB cap) consists of a cylindrical aluminum or copper shell containing a series of powder charges (Figure 28). Electric current is supplied to the cap by means of two leg wires that are internally connected by a small length of high-resistance wire known as the bridge wire. The bridge wire serves a function similar to the filament in an electric light bulb. When a current of sufficient intensity is passed through the bridge wire, the wire heats to incandescence and ignites a heat-sensitive flash compound. Once ignition occurs, it sets off a primer charge and base charge in the cap near instantaneously. Instantaneous EB caps are made to fire within a few milliseconds (ms) after current is applied. Instantaneous caps contain no delay tube or delay element.

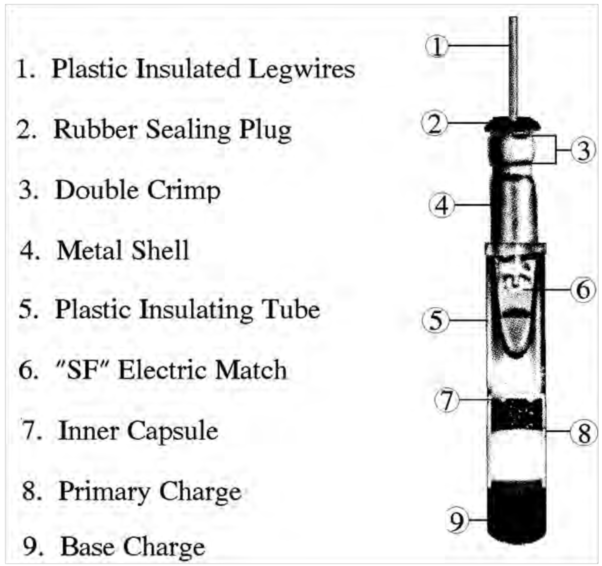

Figure 28. Instantaneous EB Cap.

Electric blasting caps with delays

A delay blasting cap contains a delay element that acts as an internal fuse. A delay element provides a time delay before the base charge fires (Figure 29). The leg wires on EB caps are made of either iron or copper. Each leg wire on an EB cap is a different color and all caps in a series have the same two colors of leg wires, which serve as an aid in hooking up. The leg wires enter the EB cap through the open end of the cap. To avoid contamination by foreign material or water, a rubber plug seals the opening so that only the leg wires pass through the plug.

Millisecond delay EB caps are commonly used for surface blasting applications (Figure 29). These delays vary between periods depending on the manufacturer. However, the most common increments are 25 and 50 milliseconds (ms). Long period delays caps are also used and have intervals ranging from a hundred ms to over a half second delay. They provide time for rock movement under tight shooting conditions. They are generally used in tunnel driving, shaft sinking, and underground mining.

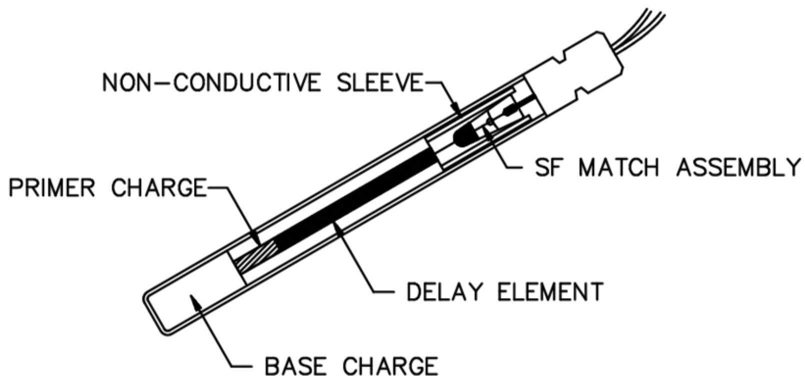

Figure 29. Delay EB Caps.

Electronic Delay Initiation Systems

The most recent development in blasting initiators is the electronic delay blasting cap. These devices allow for more accurate and precise timing than can be achieved with other initiation systems. Electronic detonators contain an integrated circuit chip and a capacitor that control the initiation time and provide voltage to the bridge wire. This provides the blaster much better control over ground vibration, flyrock, air blast, and fragmentation. These initiators virtually eliminate the problems of cap scatter times, inaccurate firing, and out-of-sequence shooting. The systems allow for both very small delays with an accuracy of ± 1 ms and for long delays up to 20,000 ms. These systems have been used on surface, underground, mining, and demolition pro- jects. These systems also allow for the blaster to simultaneously initiate two or more primers in a single column.

Electronic systems can allow a blaster to set delay timings that may be contrary to regulatory intervals (<8 ms) and regulations that control at a site should be consulted before these timings are used. Additionally, these short delay times should only be used with caution and where the blaster has significant experience with these systems and tight delays. More sophisticated blast analysis tools are also recommended where very short delays are used.

However, communication within the system can be disrupted due to stray current, leak- age, or static electricity. This can result in failed or incorrect communications or commands. Low battery levels are a particular problem and should be avoided. Manufacturers often require training and certification before these systems can be used to minimize these kinds of problems and troubleshooting can be difficult for untrained personnel.

Sequential Blasting Machine.

The sequential blasting machine was first developed by Research Energy of Ohio, Inc. It is solid state condenser-discharge blasting machine with a sequential timer that permits the detonation of many electric caps. The machine is capable of firing up to 225 ohms per circuit, at different, precisely timed intervals. The machine consists of 10 different firing circuits that are programmed to fire one after another at selected intervals. The combination of 10 different circuits, or intervals, in conjunction with delay blasting caps, can yield many independent blasts

Sequential timers are used in construction as well as mining applications. The timers al- low the use of many delays within a blast. The weight of explosives fired per delay period can be significantly reduced to control noise and vibration effects since there are many delays available. The sequential blasting machine can be set to fire from 5 to 199 ms in increments of 1 ms.

The programmable sequential timer allows the machine to be set with nine different de- lay increments. The machine also allows for the use of four slave units with the master unit. Using slaves and the master unit, one can get 50 different delays that are fully adjustable.

Electronic Delay Blasting Caps

Over the years, a definite need has surfaced for extremely-accurate delays. Electronic technology has advanced to the point that technology exists to create these accurate electronic delays at a reasonable cost. An electronic detonator with extremely-accurate firing times and the ability to have infinite delay periods at any interval of time can revolutionize the blasting industry. This initiation system would virtually eliminate the problems of cap scatter times, inaccurate firing and out-of-sequence shooting.

There are approximately a dozen different electronic detonator systems either in development or in use today. There are many differences in construction, timing precision, and methods of hookup and use. Electronic detonators can be grouped into two categories: Field programmed systems and factory programmed units. The factory programmed systems can be further grouped into electrically wired systems and systems, which use shock tube lines to energize electronic detonator.

Electronic Detonators are used at some quarries on a production basis despite of their high cost. Users claim that fragmentation is more uniform, muckpiles are predicable in shape, back walls are less damaged and vibration can be significantly lower and more predictable than when using other non-electronic detonators (Figure 30).

Figure 30. DavyFire Electronic Blasting Cap.

Non-Electric Initiation Methods (NONEL).

Non-electric initiation systems (NONEL) have been used in the explosive industry for many years. Cap and fuse, the first method of non-electric initiation, provided a low cost, but hazard prone system. The cap and fuse system has declined in use with the introduction of more sophisticated, less dangerous methods. Truly accurate timing with cap and fuse is impossible. The cap and fuse system has no place in a modern construction industry and must not be used on USACE pro- jects.

Some frequently used non-electric initiation systems are available: (1) Detonating Cords and Systems, (2) Delayed Primers, and (3) Shock Tube Initiation Systems. All are used in the construction industry. To increase the number of delays available, individuals often combine the use of more than one non-electric system on a blast. Often electric and non-electric system components are combined to give a larger selection of delays and specific delay times.

Detonating Cord and Compatible Delay Systems.

Detonating cord is a round, flexible cord containing a center core of high explosive, usually PETN (Pentaerythratol tetranitrate), within a rein- forced waterproofing covering. Detonating cord is relatively insensitive and requires a proper detonator, such as No. 6 strength cap, for initiation. It has a very high velocity of detonation approximately equal to 21,000 ft/s. The cord's detonation pressure fires cap sensitive high explosives with which it comes into contact. Detonating cord is insensitive to ordinary shock and friction. Surface as well as in-hole delays can be achieved by proper delay devices attached to detonating cord. A major disadvantage in the use of detonating cord on the surface is the loud crack as the cord detonates, and the possibility of grass and brush fires in dry areas.

Shock Tube Initiation Systems.

A shock tube is a non-electric detonator in the form of a small diameter hollow plastic tube. This tube shocks the explosive through the use of a percussive wave traveling down the length of the tube. It usually contains a small amount of Octahydro-1,3,5,7- Tetranitro-1,3,5,7-Tetrazocine (HMX)/aluminum explosive powder on the tube's inner diameter, which detonates at great speed. These systems take a precise energy input to initiate the reaction in- side the tube. It may be initiated by detonating cord, EB cap, cap and fuse, or a starter consisting of a shotgun primer in a firing device. The unique aspects of shock tube systems are:

- They are safe from some electrical hazards and radio frequency hazards.
- They are noiseless on the surface.
- They will not initiate cap sensitive explosives in the blastholes.
- They will propagate a reaction through and around tight kinks and knots.

Long Period Shock Tube Initiators provide precise non-electric delay initiation for all underground mining, shaft sinking, and special construction needs. The delay caps are available in different lengths of the shock tube. Shock tube detonators are suited for use with commercially available dynamites, cap sensitive water gels, or emulsion type high explosives because the tube will not initiate or disrupt these explosives. Shock tube initiators can be used for initiation of non-cap sensitive blasting agents with a suitable primer.

Long length, heavy duty (LLHD) millisecond initiators are similar to the Long Period (LP) initiators except that their delays are of shorter intervals. The LLHD unit has a long length tube that extends to the collar of the blasthole. The long length tube eliminates the need for any detonating cord in the blasthole that allows the use of cap sensitive explosives in the hole. Trunkline delays are usually used in place of detonating cord trunklines. All units contain built-in delays to replace conventional millisecond connectors used with detonating cord. Trunkline delays are factory assembled units with five main components, the shock tube, the blasting cap, the connector, the delay tag, and the plastic sleeve.

Lightning

Lightning is a hazard to both surface and underground blasting. Should a lightning bolt strike the blasting circuit, a detonation would most probably result with either electric, non-electric or electronic initiators. The probability that a direct hit would occur is remote, but a lightning bolt striking a faraway object could induce enough current into an electric circuit to cause a detonation. The danger from lightning is increased if a fence, stream, or power transmission line exists between the blasting site and the storm. Underground blasting is not safe from lightning hazards since induced currents large enough to cause detonations can and have been transmitted through the ground. All blasting operations should cease and the area should be guarded when a storm is approaching. Commercially available lightning detectors can be purchase in areas where electrical storms are common. Lightning Detectors are required on every construction project where blasting is required. . Equipment must be equivalent or better than the Safety Devices Model SD-250 Elk 11 (Figure 31) or the SkyScan EWSP EWS-PRO lightening detector (Figure 32).

Figure 31. Lightning Detector Model SD-250B

Figure 32. SkyScan EWSP EWS-PRO Lightning Detector.

Primer and Boosters.

The difference between a primer and booster is in its use, rather than in its physical composition or makeup. A primer is defined as an explosive unit that contains an initiator. For example, if a blasting cap is placed into a cartridge of dynamite, that cartridge with initiator becomes the primer. A booster, on the other hand, is an explosive unit of different composition than the borehole charge and does not contain a firing device. The booster is initiated by the column charge adjacent to it. A booster is used to put additional energy into a hard or tough rock layer (Figure 33).

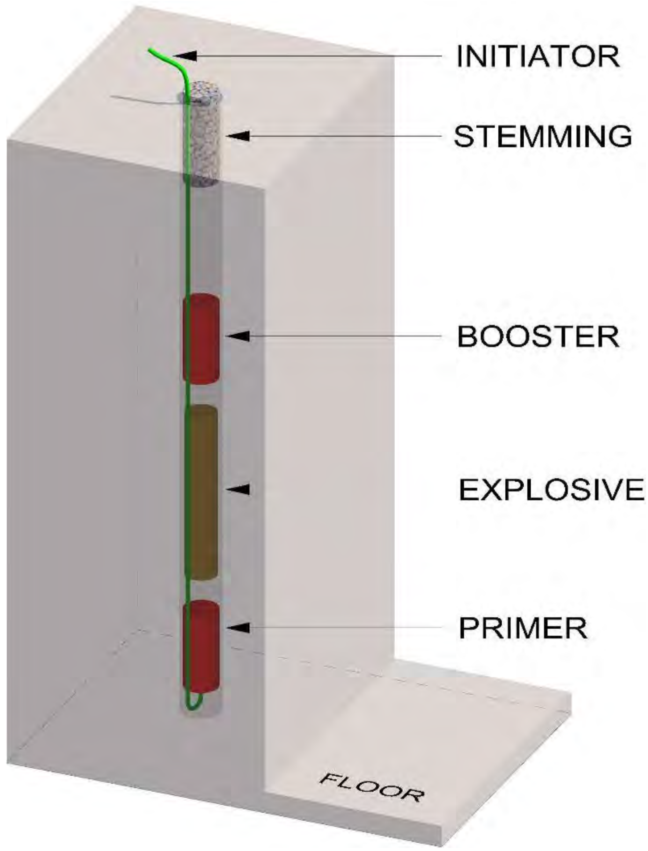

Figure 33. Primers and Boosters in a Borehole

The number of primers that placed in a blasthole is dependent on several factors. There is no one method of priming that is a universally accepted procedure. It is common practice for some operators to routinely put two primers into a blasthole regardless of the borehole length. This is done where the blaster is concerned about the possibility of getting a poor blasting cap, which may not fire, or may have a concern for cutoffs of the hole due to shifting rock caused by a previous delay firing. In either case, the rationale is that using a second primer provides insurance against problems.

If a rock mass contains considerable numbers of mud seams or open joints, confinement on the main charge could be lost during the detonation process. In this case it is common to find operators placing additional primers in the blasthole to cause the explosive charge to fire more rapidly, thereby reducing possible problems due to loss of confinement. If the blaster is working in a rock that contains mud seams, it may require a second primer to get efficient detonation throughout the total length of the charge. Conversely, in most cases from a purely technical standpoint for competent rock only one primer is needed for a single column charge of explosive. In these cases where more than one primer is used, it would be assumed that the bottom primer would be firing first.

If two or more primers are being placed in a blasthole, normally the second primer would be placed on a later delay period since the first primer location may be critical for the shot to perform properly. The second delayed primer would act only as a backup unit should the first one fail to initiate at the proper time.

Primers can be found in many sizes and in many varying compositions. Primer diameters can vary in size (Figure 34) and come in many different compositions. Various grades of dynamite are used as primers as well as water gels, emulsions, and densified AN compounds. Various types of cast explosives of high density, high velocity, and high costs are also used for priming. Because of the vast number of sizes and compositions of primers, it is confusing for the operator. Improper selections are often made that can cause less than optimum results. Figure 35 shows a typical primer.

Figure 34. Primers (Courtesy of the Austin Powder Company).

Figure 35. Primers with Caps Inserted Ready to Be Loaded into Blastholes.

The two most critical criteria in primer selection are primer composition and primer size. The primer composition determines the detonation pressure that is directly responsible for the initiation of the main charge. Research conducted by Norm Junk at the Atlas Powder Company has demonstrated that primer composition significantly affected the performance of ANFO charges. Figure 36 shows the effect of detonation pressure for a 30 in. diameter ANFO charge and the response of the ANFO at various distances from the primer. Thermal primers of low detonation pressure caused a burning reaction to start rather than a detonation. All primers producing detonation velocities above steady state are acceptable

Primer size is also important to obtain a proper reaction. Very small diameter primers are not as efficient as large diameter units. Figure 37 shows the effect of primer diameter on ANFO response in 30 in. diameter charges at various distances from the primers. This research conducted by Atlas Powder Company (Junk, 1968 and Morhard, 1987), decades ago, indicated that small diameter primers become inefficient regardless of the composition of the material used.

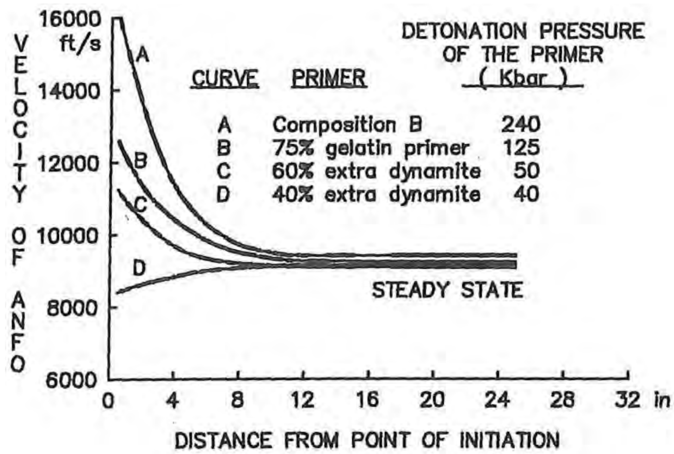

Figure 36. Velocity of ANFO with Different Primer Detonation Pressures and Distance from the Primer (Konya and Walter, 2006; after Junk).

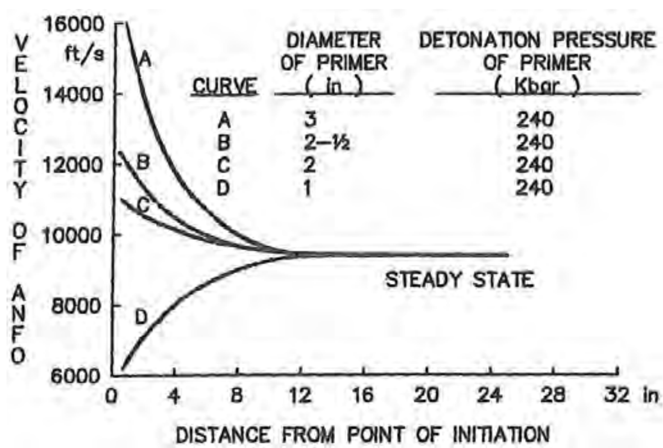

Figure 37. Velocity of ANFO with Different Diameter of Primers and Distance from the Primer (Konya and Walter, 2006; after Junk).

General guidelines for selection of a primer are:

The detonation pressure of a primer must be above the level necessary to cause the main charge to detonate at or above its normal velocity. The density and confined detonation velocity can be used as indicators of detonation pressure if detonation pressure values are not avail- able. A primer that has a density of approximately 1.2 g/cc with a confined detonation velocity greater than 15,000 ft/s will normally be adequate when priming non-cap sensitive explosives, materials such as ANFOs, blasting agents, and most water gels. This combination of density and velocity produces a detonation pressure of about 60 kbar. For explosives such as emulsions, which detonate at higher velocities, more energetic primers will produce better results. A density of primer of 1.3 g/cc with a confined detonation velocity greater than 17,000 ft/s will be adequate to more quickly achieve the explosive's normal velocity. This combination of density and velocity produces a detonation pressure of about 80 kbar.

The diameter of the primer should be larger than the critical diameter of the explosive used for the main column charge.

The primer must be sensitive to the initiator. A wide variety of the products are used as primers and each have different sensitivities. Some may be initiated by low energy detonating cord, while others may be insensitive to these initiators. It is important that the operator under- stand the sensitivity of the primer to ensure that detonation in the main column charge will properly occur.

The explosive in the primer must reach its rated velocity of detonation within the length of the cartridge. That is, the primer length should be sufficient so that the steady state velocity can be reached. If this is achieved, then additional cartridges of primer explosive serve no useful purpose.

For most blasting applications, where there is no decking, no more than two primers per blasthole are needed. The second primers, although technically not needed, is commonly used as a backup system should the first primer fail or fail to shoot the entire charge.

Boosters are used to intensify the explosive reaction at a particular location within the ex- plosive column. Boosters are sometimes used between each cartridge of detonating explosive to ensure a detonation transfer across the ties of the cartridge, but this is normally a poor use of a booster as it is seldom needed and adds to the cost. The selection of an explosive in a cartridge that would not require a booster between each cartridge may be a more economical solution.

In general, boosters are used to put more energy into a hard layer within the rock column. They are sometimes also used to intensify the reaction around the primer, which will put more energy at the primer location. This is commonly used when primers are near the bottom of the hole, since the bottom of the hole is the hardest place to break. Using a booster at the hole bottom normally allows the increase in the burden dimension and better breakage at the toe of the shot. Boosters can be made of similar explosive materials as primers. Their sole function is to place more energy at point locations within the explosive column.

Effects of detonating cord on energy release.
Cap sensitive explosives, such as dynamite, are initiated by detonating cord. Non-cap- sensitive explosives such as ammonium nitrate, emulsions, and water gels can be affected in many ways by detonating cord passing through the explosive column. If the detonating cord has sufficient energy, non-cap-sensitive explosives may detonate or burn. A burning reaction, rather than a detonation, releases only a fraction of the explosive's available energy. The blast becomes underloaded because of this low energy release and it can result in ground vibration levels in-creasing while blastholes may vent and produce flyrock.

To prevent the main explosive charge from burning or deflagrating, detonating cord should not be not too large for the borehole diameter. Acceptable cord grain loads that are not predicted to cause deflagration are given in Table 11.

Table 11. Maximum Cord Load.

Borehole Diameter (in)	Maximum Cord Load (grain/ft)
2 – 5	10
5 - 8	25
8 – 15	50

If the detonating cord is too small to cause an appropriate reaction in the explosive, it can cause the explosive to be damaged. The damage that results is called dead pressing or pre- compression. Dead pressing increases the explosive density causing it not to detonate. This occurs when the detonating cord is of sufficient energy to crush out the air spaces within the explosive or to break the air-filled microspheres placed in some products. These air pockets are needed to provide locations to form hot spots for detonation. The adiabatic compression of air is necessary for detonation to proceed throughout the explosive.

When the explosive is partially compressed or damaged by pre-compression, it may detonate or burn releasing only a fraction of the available energy. This effect can be confusing since the explosive may be totally consumed yet little rock breakage results. Commonly, the blaster who suffers this type of problem believes that the problem is because of hard, tough rock. To obtain a better understanding of this problem, look at the energy loss that results from passing a detonating cord though an explosive column in Figure 38.

Figure 38 (Bhushan. Konya, Lukovic. 1986) shows the energy loss for ANFO, which is damaged by detonating cord. Slurry can also suffer similar damage. Even a four-grain detonating cord can cause a significant energy loss in ANFO with approximately 38% of the useful energy is lost with as little as a four-grain cord in a 2-in. diameter blasthole.

The general recommendation is not to use any detonating cord in small diameter holes unless the holes are loaded with Dynamite.

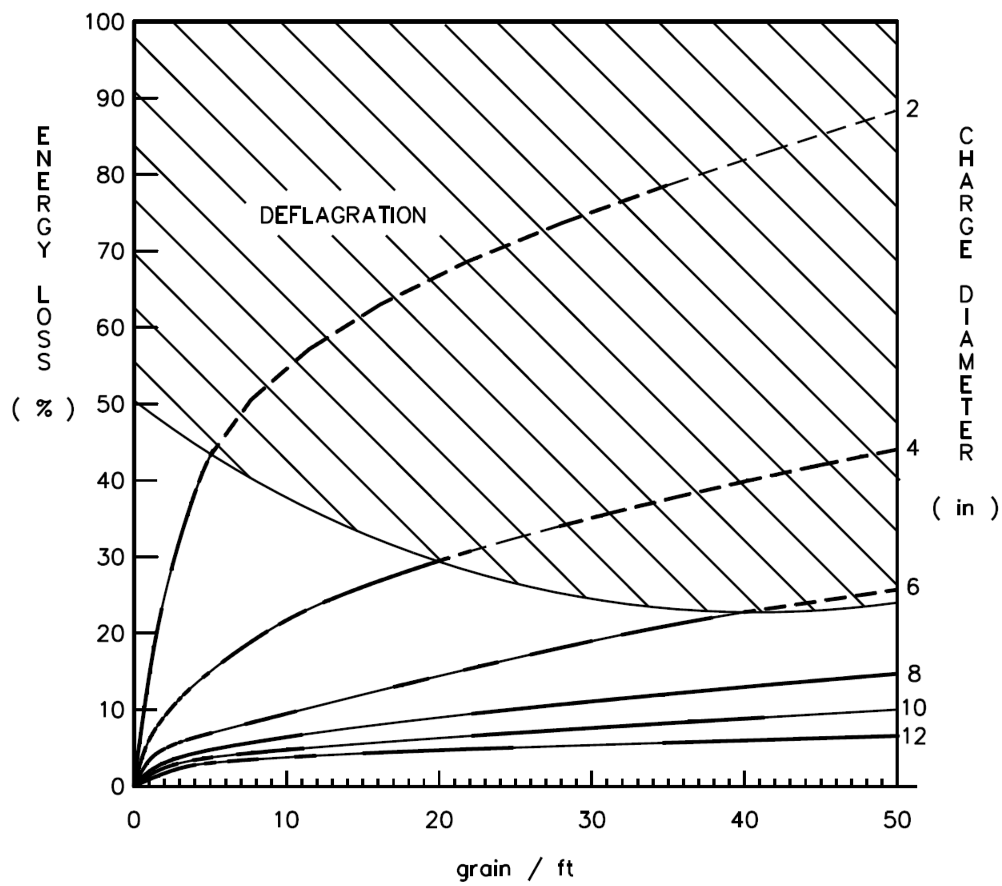

Figure 38. Energy Loss Caused by Detonating Cord (Bhushan, 1986).

Handling, Storage, and Transportation Issues.

Handling, storage, and transportation of explosives must be in line with the prescribed Federal regulations, per the USACE EM 385-1-1, Safety and Health Requirements, applicable state laws and regulations, and any local restrictions. All USACE projects as of the 2014 edition of EM 385-1-1 require that an Explosive Safety Site Plan be filed and approved with the Department of Defense Explosive Safety Board. These laws and regulations are needed to protect the safety and welfare of the public and of all personnel involved in the handling, storage, or transportation of explosives.

These regulations and requirements change based on the location of the project and may change over time. The following are a list of the Federal regulatory agencies and industry standards that should be consulted when dealing with explosives:

(1) Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF).

(2) 27 Code of the Federal Regulations (CFR) 555 – ATF Commerce in Explosives.

(3) Occupational Safety & Health Administration (OSHA).

(4) 29 CFR 1910.109 – OSHA Explosives and Blasting Agents.

(5) 29 CFR 1926 Subpart U – OSHA Blasting and the Use of Explosives.

(6) Department of Transportation (DOT).

(7) U.S. Coast Guard (USCG).

(8) Federal Aviation Administration (FAA).

(9) Department of Defense (DoD).

(10) DoD 6055.9-STD – Ammunition and Explosives Safety Standards.

(11) U.S. Army Corps of Engineers (USACE).

(12) EM 385-1-1 Section 29 Blasting.

(13) EM 385-1-97, Chapter II, "Explosive Safety for Construction Activities."

(14) American Society of Safety Engineers (ASSE).

(15) American National Standards Institute (ANSI)/ASSE A10.7 – Safety Requirements for Transportation, Storage, Handling and Use of Commercial Explosives.

(16) Institute of Makers of Explosives (IME).

(17) Safety Library Publications.

Geology and Blasting.

A thorough understanding of the geology and rock mass structure at any blasting site is fundamental to well-engineered blast design. Rock type, change in lithology, the presence of voids and the presence of discontinuities, and in rare cases the in-situ stress in the rock can all affect a blast and, when unanticipated, can affect the success of the project. Good characterization of the rock at the site and checks on that understanding by review of blasthole drilling are needed to ensure that the blast design is appropriate for the site. This section covers some of the geologic considerations for blasting, including the effects of rock type, rock mass structure, weathering, and groundwater. It assumes good familiarity with geology including rock types and structural geological conditions that can be expected at a site where a blasting program may be executed.

It concludes with a discussion of the exploration and site characterization needed to support blasting projects.

Effects of Rock Type.

Rock type can have an effect on blasting operations in that different rock types have different strengths and densities, and thus require a different blast design to achieve good results. One very interesting property of rock is that, like concrete, it is stronger in compression than in tension. Therefore, a goal of efficient blast design will be to place the rock in tension rather than compression. However, with increasing confinement, the rock becomes very strong. Thus, to move the rock by blasting, it must have a small enough burden to be displaced by the explosive.

The intact rock describes the fundamental rock type and properties (e.g., limestone and compressive strength of 5500 psi). The rock mass includes the intact rock along with all discontinuities, joints, faults, bedding, voids, etc. that occur within a volume of rock to be studied or blasted. These breaks in the rock have a significant effect on blasting operations.

While the rock mass properties are often of much more importance, the intact rock values should also be taken into account during blast design. Samples of rock, taken by diamond core drilling without the discontinuities or structure of the rock mass are generally used to deter- mine these properties. A word of caution on rock sampling of this type, as is described in many textbooks on the subject; there can be considerable variation in samples from location to location and these are very small samples when compared to the overall quantity of rock present at a site. Where limited testing is performed, more variability of results can be expected. Charts and tables for approximate values based on the rock type (e.g., granite, limestone, sandstone, shale etc.) are readily available, though the values can have a wide range and laboratory testing will better reflect actual site conditions. However, for initial estimation where laboratory tests have not yet been performed, these can be of considerable value to the designer as the first estimate of the properties. Table 12 lists some typical intact rock sample values. The following sections describe several testing methods to determine commonly used intact rock properties as pre- scribed by the American Society for Testing and Materials (ASTM 2008a,b).

Table 12. Typical Intact Rock Values (Zhou, 2008).

Rock	UC Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Poisson's Ratio	Strain at Failure (%)	Point Load Index $I_{s(50)}$ (MPa)	Fracture Mode I Toughness
Igneous							
Granite	100 – 300	7 – 25	30 – 70	0.17	0.25	5 – 15	0.11 – 0.41
Dolerite	100 – 350	7 – 30	30 – 100	0.10 – 0.20	0.30		>0.41
Gabbro	150 – 250	7 – 30	40 – 100	0.20 – 0.35	0.30	6 – 15	>0.41
Rhyolite	80 – 160	5 – 10	10 – 50	0.2 – 0.4			
Andesite	100 – 300	5 – 15	10 – 70	0.2		10 – 15	
Basalt	100 – 350	10 – 30	40 – 80	0.1 – 0.2	0.35	9 – 15	>0.41
Sedimentary							
Conglomerate	30 – 230	3 – 10	10 – 90	0.10 – 0.15	0.16		
Sandstone	20 – 170	4 – 25	15 – 50	0.14	0.20	1 – 8	0.027 – 0.041
Shale	5 – 100	2 – 10	5 – 30	0.10			0.027 – 0.041
Mudstone	10 – 100	5 – 30	5 – 70	0.15	0.15	0.1 – 6	
Dolomite	20 – 120	6 – 15	30 – 70	0.15	0.17		
Limestone	30 – 250	6 – 25	20 – 70	0.30		3 – 7	0.027 – 0.041
Metamorphic							
Gneiss	100 – 250	7 – 20	30 – 80	0.24	0.12	5 – 15	0.11 – 0.41
Schist	70 – 150	4 – 10	5 – 60	0.15 – 0.25		5 – 10	0.005 – 0.027
Phyllite	5 – 150	6 – 20	10 – 85	0.26			
Slate	50 – 180	7 – 20	20 – 90	0.20 – 0.30	0.35	1 – 9	0.027 – 0.041
Marble	50 – 200	7 – 20	30 – 70	0.15 – 0.30	0.40	4 – 12	0.11 – 0.41
Quartzite	150 – 300	5 – 20	50 – 90	0.17	0.20	5 – 15	>0.41

The density of rock is perhaps the most commonly used property as it can be used in empirical formulas to determine design powder factors. In general, the higher the bulk density of the rock, the more explosive energy will be needed for desired fragmentation. The sonic wave velocity is also typically higher for competent rock that has greater density.

Strength of the rock is usually described by the relatively simple and inexpensive unconfined compression test (ASTM D7012, Method C 2014). While the compressive strength of the rock is greater than in tension or shear, empirical values and ratios can be used to obtain the de- sired strength based on the rock type where only unconfined compression tests are performed. These are less accurate than actual laboratory tests.

Tensile strength is usually determined by the Brazilian Disk Tension test (ASTM 3967). Direct shear tests (ASTM 5607-08) can also be performed. However, the ease of rock breakage in tension is only partly due to rock being weaker in tension than in compression. It is also due to the fact that the rock is easier to fracture in tension as it is a brittle material. Explosive gases in a borehole, where there is a free face, load the rock mainly in tension, thus using far less energy than would be required if breaking the rock primarily in compression.

Tests to determine the elastic modulus (Young's Modulus) and Poisson's Ratio (ASTM D7012, Methods B and D 2014) are performed and have been used to determine the blastability of rock.

Effects of Rock Mass Structure.

While laboratory samples may test the intact rock, the actual strength of the rock mass and its resistance to blasting are usually far less than the intact rock values would indicate. This is due to the naturally occurring network of joints, bedding, faults, cavities, voids, and breaks within the rock. These flaws in the rock play an important role as they can create planes of weakness within the rock mass that will influence the fragmentation of the rock. Where a rock mass contains multiple rock types, or different facies, these too can influence the blast as different rock types may require different blasting design. Cavities and voids, which are a weathering feature, will be discussed below.

Structural discontinuities such as joints, faults, and bedding planes are all breaks that subdivide the rock. Their spacing, orientation, and persistence in the rock mass are the most important geologic consideration that will affect blast performance. Good mapping and site characterization is essential as the characteristics of these features will need to be communicated to the blast designer. The strike, dip, and spacing of these structural features should be well understood by the geologist before blasting design begins. The simple block diagram in Figure 39 shows how the terms are used.

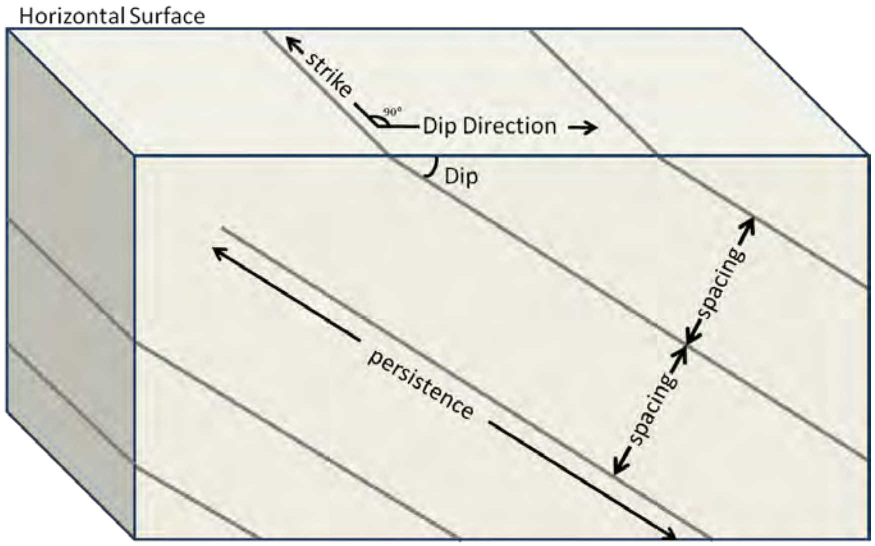

Figure 39. Strike, Dip, Spacing, and Persistence of Structural Features in Rock.

Structural discontinuities can have an aperture (opening) and infilling of material such as clay. Where the aperture is small and there is little infilling, this may be less important than the spacing. However, as will be discussed, these features can serve as a conduit for water, and weathering effects can widen them to significant features.

The block size and fragmentation characteristics of the rock mass are heavily influenced by the spacing of these discontinuities (Figure 40.). Explosive energy will not be well distributed through the rock mass when the borehole patterns are larger than the discontinuity spacing. When the borehole separation is 2 to 4 times the block size, much larger boulders with inadequate fragmentation that are difficult to handle can be expected. More effective fragmentation is accomplished where explosive charges lie within the solid blocks bounded by joints. This is typically adjusted by tightening the pattern and using a smaller blasthole diameter.

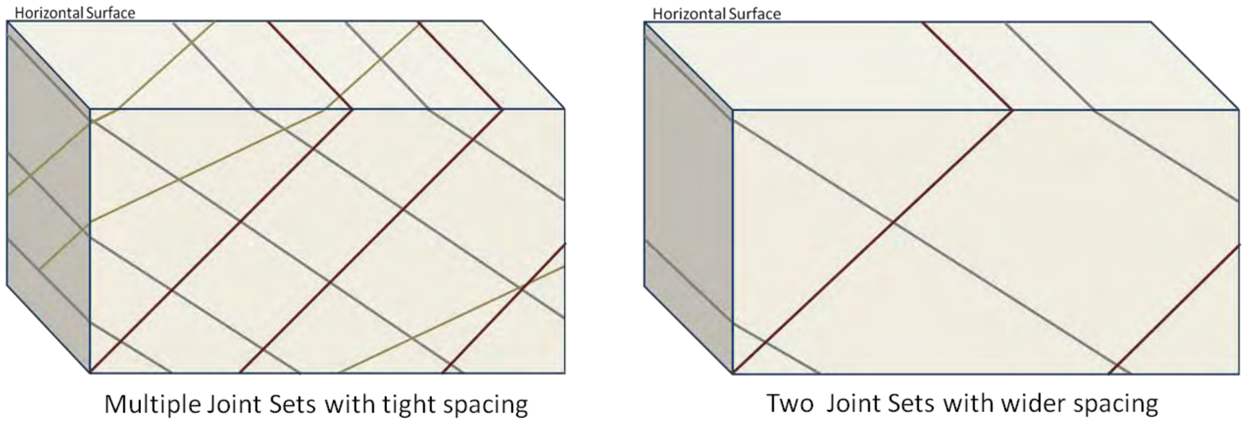

Figure 40. Comparison on Block Size in Rock Mass with Different Joint or Discontinuity Sets and Spacing.

Additionally, the tensile strength across a structural discontinuity is considerably weaker than the tensile strength of the intact rock. Thus, where borehole spacing is too wide, instead of forming the tensile cracks through the intact rock, the mass splits along the discontinuity instead of the desired rock face. This can lead to a widening of the aperture of the discontinuity, leaving a structural feature in the remaining rock mass that can contribute to long term stability problems.

This can be particularly problematic for presplit faces. Where discontinuities are nearly vertical and strike parallel or within around 15 degrees of the direction of the final rock face, it can be extremely difficult to create a presplit face that does not follow these discontinuities.

The overall dip of the structural features present in the rock mass in relationship to the desired bench or final wall face can make a difference in the final wall produced. Blasting with the dip or against the dip can both leave rock slope stability vulnerabilities in the final rock wall. Blasting with the dip can allow for the use of lesser explosive charges, or use larger burdens as the rock moves more readily down the slope. However, this can produce much greater back- break at the top of the slope. Where the discontinuities may intersect the top of the slope or next higher bench behind the desired face, the rock may be removed along the dip, rather than at the design face location. Figure 41 shows backbreak where rock is removed at the top of the slope beyond the design face. Blasting against the dip generally requires more explosive charge as the blast must work against the overall rock mass structure. However, this can produce more over- hangs.

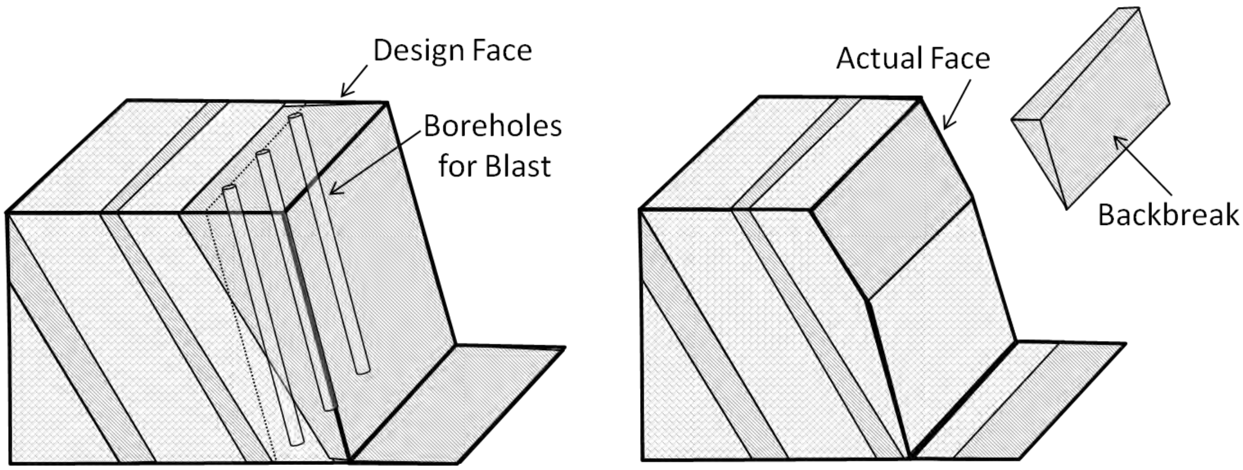

Figure 41. Blasting with the Dip Where Backbreak Removes Additional Material at the Top of the Slope.

Figure 42 shows overhang that can occur from backbreak of material removed at the bottom of the slope when blasting against dip. Where more lightly loaded to prevent the back- break at the toe, additional material can be left on the slope at the toe. Blasting can also be executed against strike, though where multiple rock types are present in the face, the results can be somewhat unpredictable. The block diagram in Figure 43 illustrates this.

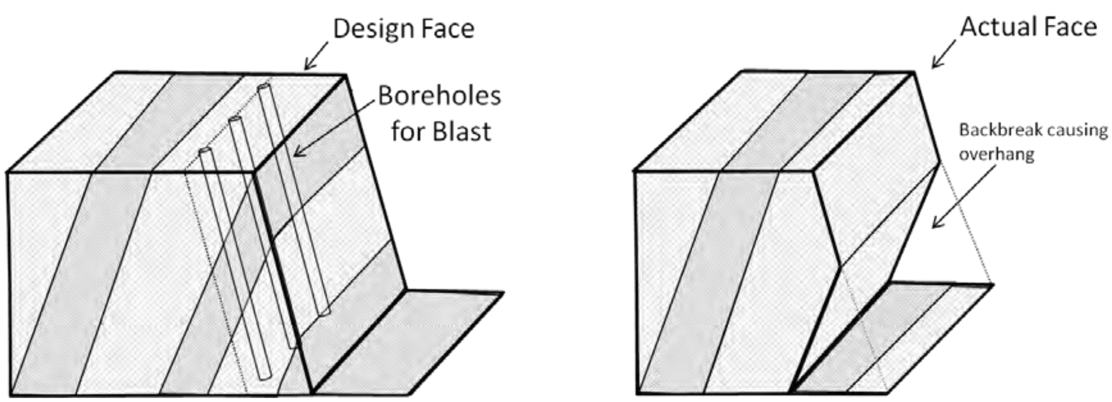

Figure 42. Blasting against Dip Where Backbreak Occurs at the Toe of the Slope Causing and Overhang.

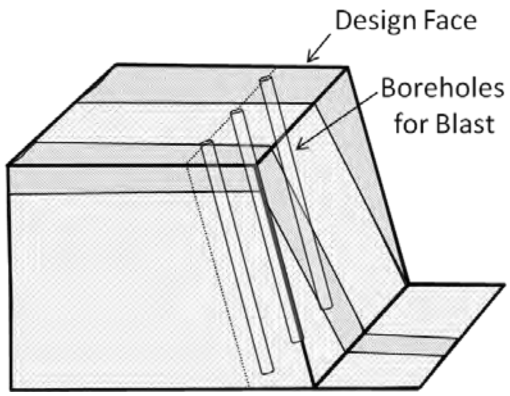

Figure 43. Blasting Against Strike.

Figures 41 to 43 show that the structure of the rock should be taken into account when planning a blast design because the structure can have a strong influence on the stability of the wall. Kinematic analysis of the rock structural features should be completed during the design phase of a project where rock excavation is planned to identify problem features that may develop in the design rock wall or excavation.

Figure 44 shows rock stability failure modes that can be created by rock removal and expo- sure of rock structural discontinuities. Design of the site should incorporate a thorough understanding of the rock structure and problems that can develop during construction. A review of the bore- holes used for blasting as the project progresses should be used to check the original geological model for the site. A final wall should always be inspected after a blast to assess the rock slope stability and determine the need for any additional blasting, mitigation, or reinforcement.

Where a rock mass to be blasted contains more than one rock type, blasting can become more complicated as each material may require a different powder factor and design to achieve good results. The stratigraphy of the site should be well understood during the design process as the blasting techniques may need to be modified for each rock type present. Deck loading is of- ten used to accommodate changes in stratigraphy.

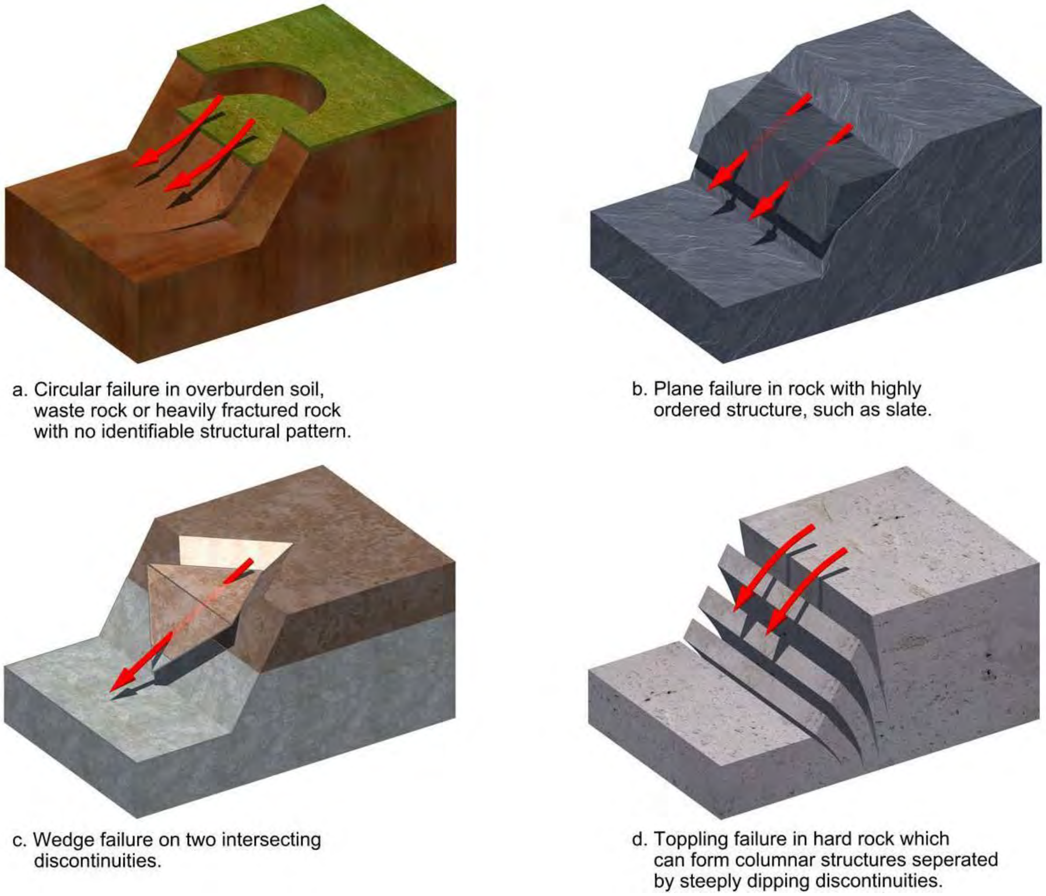

Figure 44. Rock Failure Modes Due to Structure within a Rock Mass.

Removal of the confining rock can also cause problems in the remaining rock mass, particularly where the in-situ horizontal stress is high. Figure 45 shows a tension crack along a pre- split wall and Figure 46 shows heave in a quarry floor. These features are often also structurally controlled as they occur most easily along the weaker discontinuities in the rock and perpendicular to the major principal stress.

Fault zones also present a problem, particularly where they enclose breccias. Blasting conducted near faults will often break to the fault surface. Venting of gases can also occur along permeable breccias or fault zones, causing a loss in the blasting energy and poor results unless deck loading is used. Porous faults and breccias constitute potentially weak zones that may be of utmost importance in stability considerations.

Figure 45. Tension Crack in Rock Mass after Presplit Blasting.

Figure 46. Heave in Quarry Floor Due to Unloading of the Rock by Blasting and Excavation.

Effects of Weathering on Blasting Operations.

Voids (openings, cavities, and caves in rock) can have a deleterious effect on blasting. These voids can be naturally occurring as in karst rocks such as limestone, or they may be manmade due to tunnels, shafts, pipes, or abandoned mines. Where any karst sensitive rock such as limestone, gypsum, anhydrite, or dolomite are expected at an excavation site, the geologist assessing the site should provide a description of the solutioning activity expected. Figures 47 and 48 show some problem karst features encountered during a blasting project.

Figure 47. View of Karst Feature at Base of Presplit with Concrete Added at Cave Mouth.

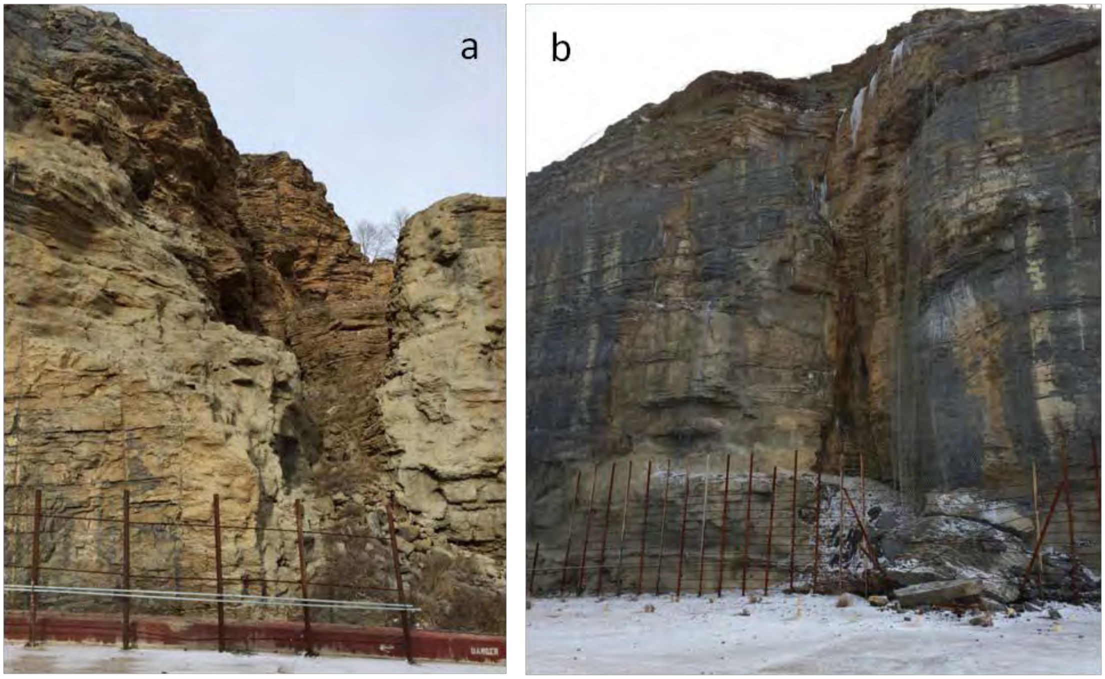

Figure 48. Vertical Karst Features in Presplit Face.

Careful attention will be needed to drilling for the blasting boreholes as it is seldom possible to fully map a site and describe the location of every possible void and cavity. Furthermore, while the karst development at the site may be described, solutioning can be expected to occur along structural features in the rock. It is not unusual for cavities to occur along bedding or along joints. Where two joints intersect, a karst shaft may develop. This information along with the drill logs will be of great value to the blaster. However, to assess the effects of blasting on surrounding structures and the final wall excavation, a geologist or engineer assigned to monitor the construction should also review all of this data before the holes are loaded.

Explosives can be lost into a void, particularly those in bulk or slurry form resulting in overloading. The air space can decouple the explosive and rock, decreasing the deficiency of the blast. Voids can cause a blast to have inadequate confinement, which can lead to additional fly rock. Where voids, either manmade or natural, are connected to the surface, unexpected air overpressure may be broadcast out of the void and onto the surface.

Where bulk explosives and slurries are used, the blaster should keep a careful account of the amount of explosive material that went into the hole. Drilling and blasting records are key to recognizing these conditions before loading of holes. Drillers will often record voids as “rod drops” that is a zone where there was little or no resistance to drilling. If loss of explosives into a void is suspected, the zone should be located and corrective measures taken to seal it. Special handling of the loading will be required where cavities are encountered; the loading may be plugged in the borehole above and below the cavity, or it may be sealed with sand, stemming material, or grouting. It may be necessary to prohibit use of bulk explosives on projects where there are numerous voids and cavities. This can be addressed through the plans and specifications.

Likewise, zones of intact but weathered rock can present difficulties to the blaster. Mud seams and weathered zones have different properties than the unaltered and intact rock. Weathered rock will blast more easily than a massive intact rock, so blasting techniques should be adjusted. Typically, the blaster may lower the powder factor when working in this type of material. Figure 391 shows some weathered limestone layers uncovered by excavation during a blasting project. The limestone in this photograph is substantially weathered, and numerous karst features are present.

One way of simplifying the handling of weathered material is to blast it separately from the intact material below. By partially excavating down to the lower limit of a weathered zone, the mass is simplified to one with fairly uniform properties. The type of explosives used for excavating weathered material will vary based on the extent and degree of weathering, but generally, the blaster may use cartridged rather than bulk explosives in this type of formation. The normal situation is that the weathered zone is at or near top of rock. The difficulty in producing a good final face is compounded here by the poorer quality of rock and the lower confining pressure. There- fore, the topmost presplit bench usually requires extra care in design and execution.

Figure 49. Weathered Limestone Layers Uncovered by Excavation during a Blasting Project.

Some weathered rock is decomposed to the extent that it may be ripped (removed mechanically) or treated like a soil, negating the need for blasting. The design engineer should check the specifications of the available equipment (usually obtained from the manufacturer or supplier) before determining if the rock should be blasted or ripped. For comparison, Table 3-2 lists basic rock hardness properties and their relation to excavation techniques. Also, the designer should consider that other factors such labor, equipment costs, and total project time might be involved in determining whether rock can be ripped economically.

Mixed ground conditions, where rock "floaters" and intact rock are surrounded by soil or more weathered rock can present significant problems as these may be difficult to excavate with conventional equipment and problematic to blast. The depth and lateral extent of mixed conditions should be mapped before the blast design, and this information provided to the con- tractor in the specifications. Typically, all overburden will be removed from the rock before blasting starts in order to design and use appropriate blasting techniques. A blaster should not be allowed to blindly drill blast patterns in areas of mixed ground conditions.

These ground conditions will affect not only the design of the mass blasting, but also how the final walls are approached by the blaster. However, a few points are important to discuss here. Pre-splitting will typically be used to provide a relatively smooth finished wall. The loading of the presplit holes may need to be changed or eliminated based on the drilling and encountering voids. Typically, line drilling or precision pre-splitting will be employed at certain distances on either side of the void or other geologic feature. This will provide a finished surface.

Keeping the explosives away from the feature will prevent gases from escaping into the feature, thereby preventing unwanted effects.

Table 13. Rock Hardness and Excavation Characteristics (after Hatheway 1997).

Rock hardness description	Identification criteria	Unconfined compressive strength (psi)	Seismic wave velocity (ft/s)	Excavation properties
Very soft rock	Material crumbles under firm blows with sharp end of geologic pick; can be peeled with a knife; too hard to cut a triaxial sample by hand. Pieces up to 3 cm thick can be broken by finger pressure. Standard Penetration Test (SPT) will refuse.	250 – 440	1,500 – 4,000	Easy ripping
Soft rock	Can be just scraped with a knife; indentations 1 mm to 3 mm show in the specimen with firm blows of the pick point; has dull sound under hammer.	440 – 1,500	4,000 – 5,000	Hard ripping
Hard rock	Cannot be scraped with a knife; hand specimen can be broken by pick with a single firm blow; rock rings under hammer.	1,500 – 2,900	5,000 – 5,900	Very hard ripping

Very hard rock	Hand specimen breaks with pick after more than one blow; rock rings under hammer.	2,900 – 10,000	5,900 – 7,000	Extremely hard ripping or blasting
Extremely hard rock	Specimen requires many blows with geological pick to break through intact material; rock rings under hammer.	> 10,000	> 7,000	Blasting

Effects of Ground Water on Blasting Operations.

Ideally, every blaster would prefer that all boreholes be dry. However, this is seldom the case. Water in a borehole creates problems in that it limits the explosive products that can be used. Explosive products that float or are not water resistant will interfere with blasting operations where water can be expected in the blasting boreholes. Where the blaster uses low water resistance explosives, the boreholes must be dewatered before loading and protected from water reentry. Even small amounts of water can degrade most ANFO products. The blastholes may be loaded with water resistant ANFO or can be redesigned and loaded with pumped bulk emulsion. Water resistant cartridged explosives could also be used but will increase costs.

Where excavations are deep or underground, entire dewatering systems may need to be set up and protected during blasting operations. The need for site dewatering should be ad- dressed during the site characterization and should be included in the plans and specifications. As of 2015, the most common way of dealing with dewatering at a site is to require a contractor to assess the dewatering necessary and propose a plan to USACE personnel in the form of a submittal. This method has certainly been used with great success on many projects. However, the need for dewatering and the extent of the dewatering expected should also be quantified to the extent possible during the design process and the information gathered communicated to the con- tractor. Inclusion of measurement and payment and separate contract line item numbers (CLINs) for dewatering should be very carefully formulated as they have resulted in excessive and unnecessary costs on some projects.

Pre-blast well surveys are often needed where wells are used for water supply near a blasting site. These are usually conducted by the contractor before blasting, but well surveys completed before construction can give the geologist or engineer a good idea of the surrounding groundwater conditions. Where artesian conditions are expected, this information should be communicated to the contractor in the plans and specifications.

Site Exploration and Characterization for Rock Blasting Projects.

Good site characterization of a potential blasting excavation is essential to the success of the project. There are many excellent references available on this topic, but a few important points follow.

Defining the Rock Mass

As the structure of the rock can have such a significant effect on the success of a blasting program, care should be taken to fully define the structural characteristics of the rock. This will usually involve drilling, mapping, laboratory testing, and exploration while a project is in the design phase and before plans and specifications are completed. Rock structure exists in three dimensions and any exploratory program should keep that well in mind.

Design checks will need to be made for final wall stability and to assess the potential to undermine any surrounding structures by daylighting a structural feature that could cause a rock failure mode. Kinematic analysis and rock stability analysis should always be performed if critical structures are to be located near or beside a rock excavation, even where blasting is not used.

All rock types, stratification, voids, and water conditions should be assessed for the project and information provided to the contractor and to the blaster to allow for good blast design. Many of these features can have detrimental effects on blasting that cannot be mitigated in design if they are unexpected.

There will be a need for laboratory testing of samples. Intact rock samples should be tested in the laboratory to provide information for the blaster. ASTM laboratory testing methods listed should be used to provide the data. Published tables give a good place to begin a design, but intact rock values can be highly variable, even across a site. A published table is not adequate for final blast design.

Drilling Documentation.

Drilling is vitally important to support almost all rock excavation projects and blasting operations. Subsurface characterization is very difficult without drilling unless there are already existing rock walls that can be mapped and conditions that can be projected back into the rock mass. Angled drilling may be more effective at locating potential problems in the rock mass.
It is important that all exploratory boreholes be accurately surveyed and completely back- filled, and that all lost tools be carefully documented. The presence and condition of exploratory boreholes will need to be accounted for in the design. Poorly backfilled or open holes can destroy a shot, leading to damages and claims.

While it is seldom possible to completely replace the information from drilling with geo- physics, many geophysical tools can be used to extract the maximum amount of information from each borehole. Although it is an older method, gamma-gamma has been used successfully for many years to located shales and clay seams. Newer camera-based methods such as the Optical and Acoustical Televiewer can be of great benefit to the geologist who assesses the site because these methods reveal the true in-situ conditions of the rock. Additionally, these methods can be used to get orientations of structural features encountered in the borehole, replacing the far more cumbersome oriented core methods. Although these methods are likely impractical for use in boreholes intended as part of the blast design, thy can give invaluable site characterization data to the geologist during an exploratory program. Many other methods are available with extensive information available in published literature.

Drilling information will also be gathered during construction as the blasting program is executed. However, the boreholes drilled as the blasting proceeds should be reviewed not only by the blaster, but also by other qualified personnel such as the geologist or engineer assessing the site to determine that site conditions are as expected based on the exploration and the design. This can be particularly crucial in karst conditions where additional voids and cavities are frequently located during blasting even when the site characterization is excellent. The rock-quality designation (RQD) values, the percent recovery and the length of intact core pieces can give the blaster important information about the formation and how to load the blastholes. The blaster should review the core boxes pre-bid to be able to give a realistic blasting price.

Reports and Documents. All information gathered in the site exploration should be used to create a report that explains all of the pertinent data and conclusions based on that data. This data must be included in the Design Documentation Report (DDR) and should be incorporated to the extent possible into the plans and specifications or in attached data provided to the contractor. The particular vehicle used to convey this information to the contractor may vary based on the contracting method. However, as has been discussed in this section, it is vitally important that the blaster understand the geological conditions of the site. Site characterization information that is more interpretive may be more appropriate to include in the Engineering Considerations and Instructions to Field Personnel to provide the Quality Assurance (QA) staff the benefit of the design rationale.

Drilling Logs. The blaster is required to keep a drilling log to be able to identify unusual geologic features such a voids and soft seams in each blasthole. This is essential so that the blaster can properly load the holes. The blaster must be required to use the drilling log to pre- vent overloading weak areas ,which can result in blow outs, violence, flyrock, excessive air over- pressure and overbreak in the final walls. The drilling log should be compared to the blasthole loading diagrams to be sure that the blaster is properly loading the blastholes.

Quiz Questions

1. **Which of the following inventor was instrumental in the development of dynamite?**
   - Alfred Nobel
   - Ascanio Sobrero
   - Lammot du Pont
   - Joseph Wilbrand

2. **When the combustion of the explosive compound occurs at less than the speed of sound it is called what?**
   - Detonation
   - Detonation velocity
   - Deflagration
   - Flagration

3. **Give an example of a high explosive and low explosive?**
   - Black powder, Dynamite
   - Dynamite, Black powder
   - ANFO, blasting cap
   - Deflagration, TNT

4. **Powder factor is the ratio of?**
   - Weight of explosives to total volume of rock that was blasted
   - Weight of explosives to total weight of rock that was blasted
   - Volume of explosives to total volume of rock that was blasted
   - Black powder weight to total weight of the explosive

5. **Of the two basic forms of energy released during an explosion which one provides majority of the work?**
   - Shock energy
   - Gas energy
   - Blast energy
   - Detonation energy

6. **Referencing the figure for detonation/explosion pressure, what is the approximate detonation velocity if the calculated detonation pressure is 20 Kbar?**
   - 10,000 ft/s
   - 10 ft/2
   - 0.8
   - 10 Kbar

7. **Which of the following is not a mechanism that contributes to rock breakage in a confined charge?**
   - Shock wave
   - Gas pressure
   - Flexural failure
   - Air blast overpressure

8. **Which of the following flexure failures generally leads to desirable breakage?**
   - Top Cantilever
   - Asymmetric bending
   - Bottom Cantilever
   - None of the above

9. **A blasting operation requires removal of limestone (a soft rock), this type of dynamite would be preferred?**
   - Straight dynamite
   - High density dynamite
   - Low density dynamite
   - None of the above

10. **Dry blasting agents are most common with approximately 80% of explosives used in the United States, ANFO is a common type, what is the acronym for this?**
    - Aluminum Nitroglycerin Oxide
    - Anhydrous Nitrogen Fluorine Oxide
    - 1-Nitroglycerin 4-Oxygen
    - Aluminum Nitrate & Fuel Oil

11. A particular blasting site poses difficulties in the transportation of explosive materials to the site. What explosive should be considered?

- Low density dynamite
- ANFO cartridges
- Binary explosives
- None of the above

12. The diameter of the proposed borehole on a particular job will determine the maximum diameter of explosive column. This explosive diameter must be _________ the critical diameter of the explosive to be used in that borehole or it may not detonate.

- Equal to
- Less than
- Greater than

13. Detonation velocity is significantly less important if the explosives are used in what?

- Mud capping
- Shearing structural members
- Boreholes
- Plaster shooting

14. In the selection of explosives, the first and foremost goal is?

- Safety
- Break rock
- Environment considerations
- Cost

15. To control risk of a certain hazard, this is required on every construction project where blasting is being conducted?

- Seismograph
- Lightning detector
- Geiger counter
- Dosimeters

16. The diameter of the primer should be ________ the critical diameter of the explosive used for the main column charge.

- larger than
- smaller than
- equal to

17. The goal of efficient blast design will be to place the rock in ________ rather than ________.

- Tension, compression
- Compression, tension
- Stress, tension
- Strain, tension

18. What is the most important geologic consideration that will affect blast performance?

- Rock hardness
- Rock density
- Structural discontinuities
- Structural strength

19. What is the type of rock stability failure mode that can occur when blasting a rock with two intersecting discontinuities?

- Circular failure
- Plane failure
- Wedge failure
- Toppling failure

20. To adequately define the structural characteristics of the rock, which of the following methods should be utilized?

- Drilling
- Mapping
- Laboratory testing
- All of the above