BLASTING IN UNDERGROUND COAL MINES

by J. Edmund Hay

Supervisory Physical Scientist
U. S. Bureau of Mines, Pittsburgh Research Center

ABSTRACT

This paper presents a brief overview of safety considerations relevant to blasting in underground coal, primarily with reference to perceived problem areas in the current state-of-the-art of underground coal mine blasting. The implications for current and future research on safety in the use of explosives in underground coal mining are discussed.

INTRODUCTION

In 1984 approximately 39 million pounds of permissible explosives were consumed; almost 96 percent of this total was used in underground coal mining. The record still stands that there has never been an accident caused by permissible explosives used in a permissible manner.

This record is the result of a combined and dedicated effort by government, industry and labor. The initial impetus for the development of permissible explosives and blasting practices was the alarming frequency, three-quarters of a century ago, of mine explosion disasters which sometimes took hundreds of lives, and in which it was believed that explosives were a contributing factor. Most of the developments and specifications relating to permissible explosives and blasting practices were designed to overcome this explosion hazard.

The key elements of these developments involve the properties of the explosives and the conditions in which they are used:

A. Permissible explosives are specified and designed to have:

1. low inherent tendency to ignite natural gas/air or natural gas/coal-dust/air mixtures (incendivity)

2. high reliability in transmitting detonation from one cartridge to another

3. low sensitivity to friction

4. limited production of toxic fumes

5. controlled properties such as density, detonation rate, strength and composition.

B. Some of the practices prescribed in current regulations and schedules for their use are:

1. use of appropriate amount of stemming (at least 24 inches or half the hole depth, if latter is less than 48 inches)

2. limited weight of explosive per borehole (1.5 lbs, or 3 lbs if over 6 feet in depth)

3. minimum burden (18 inches)

4. initiation only by electric, copper-shell detonators of not less than no. 6 strength

5. firing permitted only when methane in all underground areas is less than one percent.

The intent of the above is obvious in the case of the requirements for low incendivity, friction sensitivity, and toxic fume production. The requirement for reliability of transmitting detonation is intended to minimize the occurence of undetonated explosives in the shot coal. The tolerance requirement ensures that slight batch-to-batch variations in the explosive are held within limits so that the properties that are critical to safety do not exceed safe margins. The stemming requirement, probably the most critical of all, is to momentarily hold back the hot products of detonation till they can cool somewhat by expansion into the shot coal. The limitation on the amount of explosive is intended to prevent the production of more hot products than can be retained and cooled by the stemming. The minimum burden limitation is intended to minimize too-early breakout of the detonation products (blow-through), and cut-off or ejected charges, and the initiation requirement is to provide adequate priming without introducing potential ignition sources from the initiation system. As indicated above these standards have been eminently successful in accomplishing what they were designed to do. It now remains to be considered whether there are other potential underground coal blasting safety problems which need to be addressed by research.

What follows therefore is an overview of the considerations that we in the Bureau feel are the key issues in maintaining and preserving the underground coal mine blasting safety record.

Blasting Hazards

We will consider the term "blasting hazards" to include any harmful event or hazardous situation that arises out of the handling or use of explosives, but <u>not</u> including adverse hygienic effects such as toxic fumes produced by blasting. These hazards are of two main types: direct hazards in which the detonation of the explosive itself causes damage or injury as a result of occurring at the wrong time or place or as a result of unwanted effects due to poor blast design (such as gas ignition or breaking through to an adjoining working place); and indirect effects in which the detonation (or failure to properly detonate) while not directly causing injury, sets up a situation which contributes to hazards in subsequent operations.

In the first category we have unintentional initiation of the explosive, which could occur in storage, transportation, handling at the working face, or even after loading in the shot holes before the blasting crew withdraws, or conceivably during loading out of the coal or during disposal of deteriorated explosives; in this category also as already mentioned, would be initiating gas or dust ignitions, injury to miners caused by particles of coal or rock ejected from the face, and shots which blow through to adjacent working places.

In the second category are misfires, total or partial (i.e., failure of detonation to propagate completely through the cartridge train), including those in which burning cartridges are either ejected from the face or remain in the coal, blown-out shots and roof and ground control problems caused by damage to the roof and ribs.

It might be pointed out here that, in the same round both types of hazards could occur in a chain sequence, e.g., failure of one hole to fire in an off-the-solid shot could leave the neighboring hole overburdened, causing it to blow out and thus potentially causing ignition.

These hazards are summarized in Table 1. Also in Table 1, beside each hazard an asterisk appears if the magnitude of the hazard can be affected by the particular properties of the explosive. For example, while any explosive could probably be caused to detonate prematurely by mechanical shock, some explosives are more sensitive to this than others, so this hazard has an asterisk; on the other hand, if two working faces approach each other so closely that one blows through to the other, there is nothing that can be done in the way of modifying the properties of the explosive that will minimize this: the fault is not only entirely poor design, but also cannot be "fixed" by choosing a "better" explosive. This hazard therefore does not have an asterisk.

An explanation of some of the items marked with an asterisk in parentheses or followed by a question mark in Table 1 is in order. Some misfires may be due to improper hookup of the detonators and thus obviously cannot be fixed by "improving" the explosive; equally well, some may be due to explosives which are deteriorated, and might be fixed by explosives which retain their sensitivity better under adverse conditions; therefore, the asterisk on this item is contained in parentheses to indicate partial applicability of solving the problem by improving the explosive. Similar reasoning applies to incomplete propagation of detonation. Also, although one would suppose it to be unreasonable to expect propagation through a cartridge train that has been cut off (part of the explosive cartridge train in the hole being shifted laterally with respect to the rest of the explosive by movement of the burden due to an earlier-fired hole) it is conceivable that, if the amount of shifting is not too great, sufficient shock energy could be transmitted to the remaining explosive to cause it to detonate, provided that the explosive were sufficiently shock-sensitive. The question mark indicates this as a possibility.

The point of making this distinction is to set up alternative solutions to the problem. Those hazards without an asterisk can only be addressed by greater care in the use of the explosives; those hazards which are marked with an asterisk can and should be lessened also by greater care in the use of the explosive, but here there is an additional option - the explosives themselves can be designed to be more "tolerant" of abuse, i.e., poor procedures can be partly compensated by the explosives having properties which make them less likely to contribute to the hazard.

The first approach (greater care) is properly the function of planning, training and motivating by industry and MSHA. It even offers some scope for research, but not a great deal. (For instance, one might try to determine just how close two working faces could approach one another without a blasting round in one blowing through to the other, but this would probably be found to depend on all kinds of local conditions.)

The second approach, the relationship of explosive properties to mine blasting hazards is a fruitful field for research, which is the point of making the distinction. Hereafter, only those hazards marked with an asterisk will be considered, and are considered in more detail below.

Let us now consider these hazards, particularly the ones marked with an asterisk, in more detail:

Those hazards due to untimely initiation of explosives are, at this state of the art, already minimal. The introduction of new types of permissible explosives, which may be generically referred to as non-nitroglycerin-sensitized (this includes water gels, emulsions, and explosives which are similar to nitroglycerin-sensitized explosives but which are sensitized with substances which are chemically related to but less sensitive than nitroglycerin) has made accidental initiation of explosives by heat, shock, impact, and friction even less likely than with "conventional" (nitroglycerin-sensitized) explosives, and the accident rate due to these causes was minimal even in the case of the latter. Indeed there is a point beyond which the sensitivity of explosives ought not to be reduced: that point is established by the fact that the explosive must be sensitive to the stimulus provided by the blasting cap. There remains a small probability of premature initiation due to stray currents introduced into electric blasting caps, by using inappropriate instruments to check the blasting circuit, by ground loop currents and by nearby lightning strikes. Apart from taking greater care to prevent stray currents, a possible solution would be to introduce a line of electric detonators which have greatly reduced electrical sensitivity(and this has been done in some non-coal mines), but this would involve replacing every permissible blasting unit and re-educating every shot-firer to cope with the new firing circuit parameters that would be required, and is not considered feasible.

Thus it would appear that reduction of blasting hazards in the unintentional intiation class has gone nearly as far as it can be driven by adjustment of the properties of the explosives; the balance will have to be taken care of by better planning, training, and safety motivation, and development of safer blasting practices.

The next item marked with an asterisk on the list is the possible ignition of gas or dust by blasting. This again is an area in which the primary approach to controlling the hazard is good blasting practice, in particular, observing permissible blasting practices, the most important of which are the use of the proper amount of stemming, observing the limit of three pounds of explosive per hole, and observing the proper minimum burden. Even with the measure of safety provided by these criteria, the Bureau sought over a long period of time to develop explosives whose intrinsic tendency to ignite flammable atmospheres, called incendivity, was minimal, and still assists MSHA in ensuring that all permissible explosives meet the criteria that are established to keep this property of explosives within safe limits. The success of these efforts is attested to by the statistic referred to, that there has never been a mine explosion due to the use of permissible explosives in a permissible manner. Although it would not be technically correct to say that the incendivity of permissible explosives has been reduced to the minimum possible level, it would seem to be the most effective use of research resources to investigate areas with a greater potential for causing problems.

We feel then, that the list of "direct hazards" has been virtually exhausted, and that it is in the list of "indirect" hazards that the remainder of the problems lies. When we consider those that are related to the properties of the explosive, we see that all are related, not to accidental detonation of the explosive but to the failure of explosives to detonate completely when they ought to. Here, as with all other hazards, the basic answer to the problem is care: avoiding the use of damaged or deteriorated explosives, the proper priming and loading of the explosives in the borehole, the proper hookup and sequencing of delays, checkout of the blasting circuit, and the use of permissible shot-firing units, but here again also we would like to have explosives that would compensate to some extent for deficiencies in the way that they are used. In many cases this is not possible because it amounts to wanting to save your cake and eat it at the same time. As an example, we want explosives to be relatively insensitive, so that they can tolerate some degree of accidental abuse without detonating; but, we also want the intentional detonation in the borehole to propagate from one cartridge to another even if, for some reason, the cartridges are not in contact (for instance a chip of coal or rock could get between two cartridges as they are loaded). This property of explosives, the ability to propagate detonation across a gap between cartridges, is one that is considered important enough that it comprises one of the tests for permissibility. For a new explosive to be approved as permissible it is required to propagate detonation across at least a 3-inch air gap, and a field sample (allowing for some deterioration) is required to do so across a 2-inch gap. If the explosive is too insensitive, the detonation of one cartridge may not cause the next cartridge to detonate, so solving one potential problem is not compatible with solving another.

Still, wherever possible we would like to know how to formulate explosives that would give the best combination of desired properties, and how to devise laboratory tests that would enable us to determine how explosives will behave (or misbehave) under conditions of actual use.

RECENT EMPHASES IN THE BUREAU'S EXPLOSIVES RESEARCH PROGRAM

Initiatives in the Bureau's research program in the last 5 or so years have been driven by a number of factors, most of which are interrelated:

One of these is the well-known fact that the sensitivity of most explosives decreases as their temperature is decreased and as they are compressed, provided that the compression is not too rapid or too severe: this latter effect is called "dead-pressing". When coupled with the fact that recent trends in explosive formulation have been toward explosives which are less sensitive to begin with, one then needs to ask whether we are approaching a situation in which only moderately low temperatures and degrees of compression could cause the explosive to completely or partially misfire.

Another factor was the Kite and Craynor disasters. Particularly at Kite, although it is reported that the holes were overloaded and understemmed, specific reasons were sought to explain the occurrence of the mine explosion in the particular round being blasted. When it was found that the next-to-last hole had misfired, it was theorized that the last hole, having no lateral relief (this was a case of shooting off the solid) blew out, causing the ignition. If this theory is correct, it adds considerable weight to the importance of minimizing misfires.

A third factor was the enforcement of a limit of 500 milliseconds on the total interval allowed for delay shooting. Subsequent to this, comments were received by both MSHA and the Bureau that, in order to shoot faces with a large number of holes with successive delay periods in adjacent holes (a necessity when shooting slab rounds off the solid) the individual delay periods had to be crowded together, and that when this was done, poor blasting performance, including the possibility of blown-out shots was feared, and in one case it was claimed, to be observed.

Also shortly prior to this time, a study was published by Martin-Marietta Company showing that crowded delay periods did indeed cause poor blasting performance, including blown-out shots, which appeared to add credibility to the claims mentioned above.

Furthermore, it was observed in Bureau research on the desensitization of explosives by compression, that many explosives regain their sensitivity when the pressure is released. The significance of this for the problem at hand is the following: If an explosive is fired in a borehole, the pressure wave from it, passing over and compressing the explosive in an adjacent borehole, may temporarily desensitize it; this is acceptable, if the pressure wave passes on and the desensitized explosive has the opportunity to recover before it is expected to fire; however, if the delay time between the firing of the two holes is too short, the explosive in the second hole will still be desensitized and will misfire.

Finally, it has been alleged in some quarters that instances of misfires in coal mines are on the increase in recent years. Taken together with the above considerations, this allegation is at least suggestive, and the implications of a possibility of a growing number of misfires should not be ignored. As an aside, we would appreciate receiving any data that might be available relating total or partial misfire occurrences in the field to type of explosive, hole spacing, delay periods, method of priming, etc.

One additional problem area that surfaced about the same time was the occurrence of some cases in which explosives had not only failed to detonate, but were found to be burning in the shot coal. Although these instances are very rare, the implications are very serious since the ejection of a flaming cartridge into the cloud of coal dust and natural gas produced immediately following a shot would be a very likely cause of a mine explosion. Taking the above considerations together, the following concerns became the major components of the Bureau's research initiatives:

1. Determination of the probability that detonators of adjacent periods would fire at times sufficiently close that either the coal (in an off-the-solid slab round) would have insufficient time to move out, so as to provide relief for the next hole, causing the next hole to fire in an overburdened environment, and possibly causing it to blow out, or that the pressure on the adjacent hole would cause the explosive in that hole to be desensitized, causing a total or partial misfire or deflagration.

2. Determination of the conditions of pressure and timing under which explosives might be desensitized by the pressure from detonation in an adjacent borehole.

3. Determination of the conditions under which explosives might deflagrate (undergo slow burning) rather than detonate, if initiated in a partially desensitized state.

4. Determiniation of whether problems alleged to be inherent in too-close spacing of adjacent delay periods were real, and if so, whether they could be solved by increasing the allowable delay intervals without introducing other problems.

5. Determination of conditions conducive to misfires in actual mine environments, as opposed to laboratory conditions.

The first of these objectives was straightforward to accomplish. Tests were run on several lots of each delay period of all domestic manufacturers of coal mine delay detonators, and it was found that, particularly at the high delay periods, where delay times are long but intervals are short, that there is a finite probability of detonators of nominally later periods "overlapping", i.e., firing at the same time as, or before, those of nominally earlier periods. The probability of this happening is rather small, only a few percent, but the point is established that, if there are indeed hazards associated with too-close delay intervals, steps will need to be taken to correct the overlaps.

Since improving the accuracy of the timing of delay detonators was thought to be difficult, an alternative solution was sought, namely spreading out the delay intervals sufficiently that reasonable deviations from nominal timing do not result in overlaps. Since it is necessary to shoot as many as nine or more holes to cover a face when shooting slab rounds off the solid, spreading the individual intervals out also necessarily involves increasing the overall interval beyond the 500 millisecond maximum currently allowed. It was felt by MSHA that research would be needed to support increasing the overall delay. Accordingly, field research was undertaken to determine the consequences of extending the maximum allowable overall delay interval in multiple-delay blasting in underground coal mines. This research and its results thus far are described in the following paper. The primary thrust of this research was to determine whether increasing the delay periods would have any significant effect on the possibility of igniting natural gas/air or coal dust/gas/air mixtures at the face. Someone may wonder why the ignition possibility should be related to the delay time, and the answer is that there are at least 4 possibilities.

1. Assuming that little gas or dust is present in the air before the face is shot, the only gas or dust available for ignition is that liberated by the shot itself, that is in a multiple-hole round, by the preceding holes in the round. This gas or dust has to migrate to the vicinity of the later-firing holes of the round if it is to be ignited by them, and this process takes a little time (maybe a few hundredths of a second), so that one might expect longer delays to result in richer gas/dust mixtures available for ignition.

2. On the other hand, there is an upper limit on the concentration of natural gas in air which can be ignited, (about 15 percent) and although the value of the upper flammable limit for coal dust in air has not been firmly established, the existence of such a limit has been observed. The probability of ignition would increase with the delay interval as the gas/dust concentration builds up into the flammable range, then decrease as the concentration moves into the too-rich range, then increase again as it begins to fall back into the flammable range (as a result of mixing with more air), and finally decrease as it becomes too low.

3. This is made more complicated by the fact that the products generated by the explosive are largely gases (water vapor, carbon dioxide, nitrogen) which can quench ignition, and their concentration also will initially increase, and then decrease with time.

4. Finally, if the delay interval is too short, at least in off-the-solid shooting, the coal blasted by one borehole charge will not have sufficient opportunity to move out before the next charge fires, so the next charge will fire into too tight a formation, with the risk that its products may be ejected from the hole into the surrounding gassy and/or dusty atmosphere. And, on the other hand, if the interval is too long, there might be an opportunity for the next charge in the firing sequence to be ejected from its borehole altogether (by the blast from the earlier-fired charge) before it fires, and would then fire in the middle of the gas/dust cloud, a very dangerous condition. Thus the expected behavior is very complicated.

Since an experimental approach to resolving this problem required field testing, it was thought worthwhile to use the opportunity to investigate the possible occurence of misfires in field conditions as well. This is also reported in the following paper.

It was not however considered efficient to investigate the occurence of deflagrations or to make a thorough scientific study of the misfire problem in the field, since both processes depend on a large number of factors which must be controlled if the data is to be intelligible. Indeed we have not gotten far with research on deflagration since we feel that deflagration cannot occur unless conditions conducive to a misfire already exist, and that the latter is the primary problem. At this point our research on misfires has consisted primarily of investigating the conditions under which cut-off charges occur (reported in the following paper) and a laboratory study of the desensitization of explosives by applied pressure. In this connection we have developed an apparatus which simulates the pressure and time characteristics of the pressure pulse that a charge in a borehole would experience as a result of the detonation of a charge in a nearby borehole.

Using this apparatus we have investigated the tendency of a variety of permissible explosives to be desensitized by compression, and have used it to develop a relative ranking of explosives according to their tendency to be desensitized, although resolution of the more complex question of how this desensitization depends on the time interval has not yet been completed.

CONCLUSIONS

Bureau research to minimize blasting hazards in underground coal mines endeavors to keep abreast of the state of the art of blasting technology and its associated problems. The problems addressed include those which may indirectly contribute to a hazardous situation, as well as the more obvious hazards. The Bureau's research program in this area seeks on the one hand to develop safer blasting practices while also developing specifications for properties of the explosives to give the broadest margin of safety.

REFERENCE

1. Initiator Firing Time and Thin Relationship to Blasting Performance. S.R. Winzer, W. Furth, and A. Ritter, 20th U.S. Symposium on Rock Mechanics, Austin, Texas, June 4-6, 1979.

Table 1. Underground Coal Blasting Hazards

I. Direct (detonation of explosive causes actual injury)

   A. Untimely detonation by:

      1. stray current to detonator in primed cartridge
      2. mechanical impact or shock*
      3. friction*
      4. heat*

   B. Unexpected side effects of intentional detonation

      1. blow-through to adjacent working place
      2. gas or dust ignition/explosion*
      3. miners struck by fragments

II. Indirect (detonation or failure to detonate completely sets up secondary hazard)

   A. Misfire (*)

   B. Failure of detonation to propagate completely*

      1. "channel effect"*
      2. dead pressing (pressure desensitization)*
      3. low temperature desensitization*
      4. gap in explosive train (*)
      5. cut-off charge* ?

   C. Deflagration (explosive burns rather than detonates)*
   D. Excessive damage to roof and ribs
   E. Incomplete pulling of round (leaving "brows", etc.).

*hazard varies in relation to explosive properties.

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EDITED BY:

Michael Karmis
Department of Mining and
Minerals Engineering
Virginia Polytechnic Institute
and State University

Gavin Faulkner
Department of Mining and
Minerals Engineering
Virginia Polytechnic Institute
and State University

William H. Sutherland
Mine Safety and Health
Administration
U.S. Department of Labor

David R. Forshey
Bureau of Mines
U.S. Department of the Interior

J. Richard Lucas
Department of Mining and
Minerals Engineering
Virginia Polytechnic Institute
and State University

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