



## Blasting injuries in surface mining with emphasis on flyrock and blast area security

T.S. Bajpayee\*, T.R. Rehak, G.L. Mowrey, D.K. Ingram

NIOSH Pittsburgh Research Laboratory, P.O. Box 18070, Pittsburgh, PA 15236-0070, USA

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### Abstract

**Problem:** Blasting is a hazardous component of surface mining. Serious injuries and fatalities result from improper judgment or practice during rock blasting. This paper describes several fatal injury case studies, analyzes causative factors, and emphasizes preventive measures. **Method:** This study examines publications by MSHA, USGS, and other authors. The primary source of information was MSHA's injury-related publications. **Results:** During the 21-year period from 1978 to 1998, the mean yearly explosive-related injuries (fatal and nonfatal) for surface coal mines was 8.86 (95% CI: 6.38–11.33), and for surface metal/nonmetal mines 10.76 (95% CI: 8.39–13.14). Flyrock and lack of blast area security accounted for 68.2% of these injuries. This paper reviews several case studies of fatal injuries. Case studies indicate that the causative factors for fatal injuries are primarily personal and task-related and to some extent environmental. A reduction in the annual injuries in surface coal mines was observed during the 10-year period of 1989–1998 [5.80 (95% CI: 2.71–8.89)] compared to the previous 10-year period of 1979–1988 [10.90 (95% CI: 7.77–14.14)]. However, such reduction was not noticed in the metal/nonmetal sector (i.e., 9.30 [95% CI: 6.84–11.76] for the period 1989–1998 compared with 11.00 [95% CI: 7.11–14.89] for the period 1979–1988). **Discussion:** A multifaceted injury prevention approach consisting of behavioral/educational, administrative/regulatory, and engineering interventions merits consideration. **Impact on industry:** The mining community, especially the blasters, will find useful information on causative factors and preventive measures to mitigate injuries due to flyrock and lack of blast area security in surface blasting. Discussion of case studies during safety meetings will help to mitigate fatal injuries and derive important payoffs in terms of lower risks and costs of injuries.

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**Keywords:** Blasting; Mining; Explosives; Injuries; Flyrock; Blast area security

### 1. Introduction

Mining is a hazardous occupation. The average annual rate of fatal injuries (number of fatal injuries per 100,000 workers) in the mining industry (30.3) exceeds that of all other industries, such as agriculture, forestry, and fishing (20.1), construction (15.3), transportation and public utilities (13.4), and manufacturing (4.0). In addition, the average number of days lost (ADL) per incident in the mining industry exceeds the ADL of all other industries (NIOSH, 2000). While cognizant of the inherent dangers, explosives are essential in breaking rock. Surface mines in the coal and metal/nonmetal sectors rely extensively on explosives to uncover mineral deposits. The mining industry considers

blasting an essential component for the success of their operations.

#### 1.1. Explosives used in surface mine blasting

More than 90% of the domestic explosive and blasting agent formulations generally used are ammonium nitrate (AN) based (USGS, 2000). A mixture of ammonium nitrate and fuel oil, commonly known as ANFO, gained acceptance for blasting at surface mines. The major advantages of ANFO are related to safety, economy, and ease of handling when compared to nitroglycerine (NG)-based high explosives. Various forms of NG-based high explosives were used in surface blasting before the introduction of ANFO. During the past two decades, ANFO formulations have undergone numerous innovations to improve performance, shelf life, density, porosity, specific energy, and water resistance. Since its introduction, ANFO has replaced many grades of dynamites and other high explo-

\* Corresponding author. Tel.: +1-412-386-6636; fax: +1-412-386-6561.

E-mail address: TBajpayee@cdc.gov (T.S. Bajpayee).

Table 1  
MSHA accident classification

| Class   | Source of Injury   |
|---|--|
| 1. Electrical   | Accidents in which the electric current is most directly responsible for the resulting accident.   |
| 2. Entrapment   | Accidents involving entrapment of persons.   |
| 3. Exploding Vessels Under Pressure                             | Accidents involved with bursting of air hoses, air tanks, hydraulic lines, hydraulic hoses, standpipes, etc., due to internal pressure.  |
| 4. Explosives and Breaking Agents                               | Accidents involving the detonation of manufactured explosives; includes Airdox or Cardox.  |
| 5. Falling, Rolling, or Sliding Rock or Material of Any Kind    | Accidents caused directly by falling material other than materials from the roof or face. Or, if material was set in motion by machinery, by haulage, by hand tools, or while being handled or disturbed, etc., the force that set the material in motion determines the classification. For example, where a rock was pushed over a highwall by a bulldozer and the rock hit another rock that hit and injured a worker—the accident is classified as machinery; machinery (a bulldozer) most directly caused the resulting accident. |
| 6. Fall of Face, Rib, Pillar, Side, or Highwall (from in place) | Accidents in this classification include falls of material while barring down or placing props; also, pressure bumps and bursts. Not included are accidents in which the motion of machinery or haulage equipment caused the fall either directly or by knocking out support.  |
| 7. Fall of Roof, Back, or Brow (from in place)                  | Underground only—Accidents that include falls while barring down or placing props; also, pressure bumps and bursts. Not included are accidents in which the motion of machinery or haulage equipment caused the fall either directly or by knocking out support.   |
| 8. Fire   | Accidents related to uncontrolled burning of material or mineral in the mine environment. Not included are fires initiated by electricity or by explosion of gas or dust.  |
| 9. Handling Material  | Accidents related to handling packaged or loose material while lifting, pulling, pushing, or shoveling.  |
| 10. Hand tools  | Accidents related to nonpowered tools.   |
| 11. Nonpowered Haulage  | Accidents related to the motion of nonpowered haulage equipment. Included are accidents involving wheelbarrows, manually pushed mine cars, timber trucks, etc.   |
| 12. Powered Haulage   | Accidents related to the motion of powered haulage equipment. Included are accidents involving conveyors, front-end loaders, forklifts, shuttle cars, load-haul-dump units, locomotives, railroad cars, haulage trucks, pickups, automobiles, and personnel carriers.  |

Table 1 (continued)

| Class   | Source of Injury   |
|---|--|
| 13. Hoisting  | Accidents involving cages, skips, ore buckets, and elevators. The accident results from the action, motion, or failure of the hoisting equipment or mechanism. Included are equipment such as cranes and derricks only when used in shaft sinking; also, suspended work platforms in shafts. Not included is equipment such as chain hoists, come-alongs, and winches. |
| 14. Ignition or Explosion of Gas or Dust                            | Accidents resulting as a consequence of the ignition or explosion of gas or dust.  |
| 15. Impoundment   | Accidents caused by an unstable condition or failure of an impoundment, refuse pile, or culm bank requiring emergency preventative action or evacuation of an area.  |
| 16. Inundation  | Accidents caused by inundation of a surface or underground mine by a liquid (or semisolid) or a gas.   |
| 17. Machinery   | Accidents related to the motion of machinery. Included are all electric and air-powered tools and mining machinery such as drills, tuggers, winches, slushers, draglines, power shovels, loaders, and compressors.   |
| 18. Slip or Fall of Person (from an elevation or on the same level) | Accidents include slips or falls while getting on or off machinery and haulage equipment that is not moving, and slips or falls while servicing or repairing equipment or machinery.   |
| 19. Stepping or Kneeling on Object                                  | Accidents are classified in this category only where the object stepped or kneeled on contributed most directly to the accident.   |
| 20. Striking or Bumping   | This classification is restricted to those accidents in which an individual, while moving about, strikes or bumps an object, but is not handling material, using hand tools, or operating equipment.   |
| 21. Other   | Accidents not elsewhere classified.  |

Source: MSHA (1997).

sives. Hundreds of patents related to improvements of ANFO and its loading procedures have been filed at the U.S. Patents Office. ANFO-based explosives are now available in various sizes, styles, and consistencies. Because of the diverse mechanical and geological properties of rock and the unique conditions at each blast site, a wide variety of products are available. Free-flowing dry blasting agents, with the addition of finely divided, flaked, or even granular aluminum, can be mechanically loaded in dry holes for improved performance. A variety of emulsified and gelled products are specifically designed for wet blastholes. Ingredients have been developed to improve density, rheology, sensitivity, water resistance, and detonation velocity of packaged and bulk products.

Between 1990 and 1999, roughly 22.3 billion kg of explosives were used by the mining, quarrying, construction,

and other industries in the United States (USBM, 1991, 1992, 1993, 1994; USGS, 1995, 1996, 1997, 1998, 1999, 2000). Out of this, coal mining used 66.4%, nonmetal mining and quarrying 13.5%, metal mining 10.4%, construction 7.1%, and all other users 2.6%.

### 1.2. Generic protocol for loading and firing of explosives in surface mines

Blasting is a complex activity demanding special skills on the part of the blaster and other crewmembers. It requires a careful coordination of tasks between the blasting crew and other employees working in the vicinity of the blast site. Before loading explosives in a borehole, the blaster will generally examine the drilling logs to identify potential problem areas such as presence of mud seams, voids, or geological anomalies. This is followed by a visual inspection of the highwall face and bench top. The blaster should look for presence of overhangs, back breaks, softer stratum, and other irregularities. Laser profiling data, if required, is examined at this time. Based on the approved blasting plan and the results of examination, the blaster will calculate the charge weight, geometry, stemming, and other parameters. Safety considerations dictate that employees not associated with loading and blasting operations should leave the blast site. Blast sites should be secured and warning signs posted before loading boreholes. The blasting machine or the firing key should be securely kept by the blaster during the entire process of loading and hook up to prevent any unintentional detonation. The Code of Federal Regulations (CFR), Title 30, Part 56.6306 prohibits driving vehicles and equipment over explosive material or initiating system. The rise of an explosive column in a borehole should be checked during the loading process. The blaster should know and adhere to safe operating procedures. The blaster or a designated employee should connect the individual holes to the firing line. It is a good practice to walk along the firing line to reexamine the connections. If any instrumentation for recording ground vibration and air blast has been deployed, it should be checked and set at this time.

Next, the blaster should clear all employees from the blast area, post guards at all entrances to the blast area, and communicate to the mine foreman about the impending blast. The blaster (and helpers, if any) should go outside the blast area or stay inside a blasting shelter. Upon receiving clear and unambiguous feedback from the guards and mine foreman, blast signals are sounded and the shot is fired. Rock blasting releases a tremendous amount of energy in a very short time span. It is imperative to establish an effective protocol to maintain blast area security.

Before sounding an all-clear signal, the blaster should conduct a visual inspection of the blast site and check for undetonated explosives, misfires, and other problems.

The blasting log should be finalized at this time. Finally, all unused explosives should be returned to the magazine.

### 1.3. Hazards of surface blasting

The hazards of surface blasting are primarily due to lack of blast area security, flyrock, premature blast, and misfire. Blasting generally entails two purposes: rock fragmentation and displacement of the broken rock. The displacement of the broken rock depends on the shot-design parameters, geological conditions, and mining constraints. Fragmented rock is not expected to travel beyond the limits of the blast area. The blaster determines the bounds of the blast area and is responsible for complying with safety laws. Langefors and Kishlstrom (1963), Roth (1979), and Persson, Holmberg, and Lee (1994) have developed theories to compute flyrock range. A blaster may use such concepts, in conjunction with past experience, to determine the size of a blast area.

The Institute of Makers of Explosives (IME) defines flyrock as the rock propelled beyond the blast area by the force of an explosion (IME, 1997). An injury due to flyrock is sustained when it travels beyond the blast area and injures someone. The major factors responsible for flyrock are insufficient burden, improper blasthole layout and loading, anomaly in the geology and rock structure, insufficient stemming, and inadequate firing delays. Injuries due to lack of blast area security are caused by failure to use proper blasting shelter, poor communications, and inadequate

Table 2  
Blasting injuries in surface mines, 1978–98

| Year  | Coal mines |          |       | Metal/nonmetal mines |          |       |
|-------|------------|----------|-------|----------------------|----------|-------|
|       | Fatal      | Nonfatal | Total | Fatal                | Nonfatal | Total |
| 1978  | 0          | 19       | 19    | 2                    | 21       | 23    |
| 1979  | 2          | 14       | 16    | 0                    | 12       | 12    |
| 1980  | 1          | 14       | 15    | 2                    | 16       | 18    |
| 1981  | 2          | 10       | 12    | 3                    | 8        | 11    |
| 1982  | 1          | 5        | 6     | 2                    | 6        | 8     |
| 1983  | 0          | 7        | 7     | 0                    | 5        | 5     |
| 1984  | 1          | 16       | 17    | 3                    | 18       | 21    |
| 1985  | 0          | 3        | 3     | 0                    | 4        | 4     |
| 1986  | 3          | 9        | 12    | 0                    | 8        | 8     |
| 1987  | 1          | 9        | 10    | 0                    | 14       | 14    |
| 1988  | 0          | 11       | 11    | 0                    | 9        | 9     |
| 1989  | 2          | 13       | 15    | 3                    | 11       | 14    |
| 1990  | 2          | 6        | 8     | 3                    | 13       | 16    |
| 1991  | 1          | 5        | 6     | 0                    | 11       | 11    |
| 1992  | 1          | 8        | 9     | 3                    | 3        | 6     |
| 1993  | 1          | 2        | 3     | 0                    | 7        | 7     |
| 1994  | 1          | 7        | 8     | 2                    | 8        | 10    |
| 1995  | 0          | 2        | 2     | 1                    | 7        | 8     |
| 1996  | 0          | 4        | 4     | 1                    | 6        | 7     |
| 1997  | 0          | 1        | 1     | 1                    | 5        | 6     |
| 1998  | 0          | 2        | 2     | 0                    | 8        | 8     |
| Total | 19         | 167      | 186   | 26                   | 200      | 226   |

Source: Verakis and Lobb (2001).

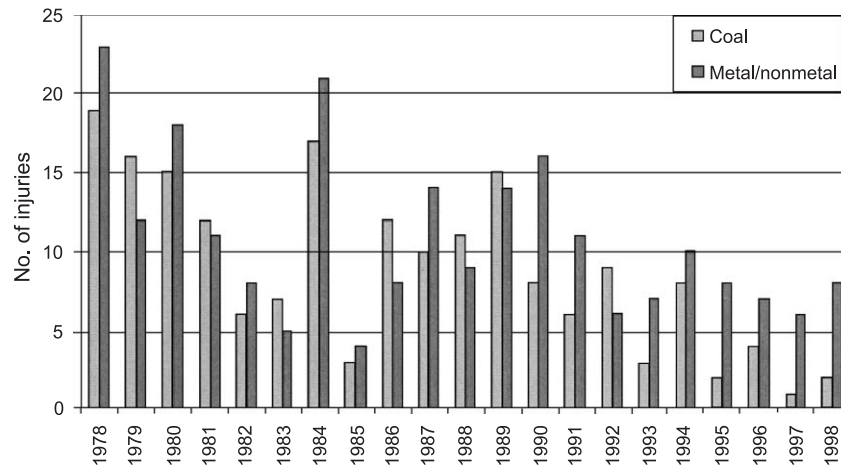


Fig. 1. Blasting injuries in surface mines, 1978–1998.

guarding of the blast area (Rehak, Bajpayee, Mowrey, & Ingram, 2001).

## 2. Methods

Mining injury and accident information was obtained from several sources. Mine Safety and Health Administration's (MSHA) injury-related publications were used as the primary source of data. Reporting requirements for injuries, illness, and workplace exposures are stipulated in the Federal Coal Mine Health and Safety Act of 1969 and the Federal Mine Safety and Health Amendments Act of 1977. MSHA's accident investigation reports were used to gather information on fatal injuries. MSHA has categorized mining injuries in 21 classes based on the circumstances that contributed most directly to the accident (MSHA, 1997). Table 1 provides a list of categories used by MSHA for accident classification. Blasting-related accidents are listed under class 4 (Explosives and Breaking Agents).

All pertinent information on loading and firing protocol of explosive charge was critically examined during field visits. Published information identified during the initial search was screened using the criteria: (a) new technology and review of recent developments to mitigate blasting injuries; (b) general information related to flyrock and blast area security; and (c) reports of accident investigations. Several publications by the U.S. Bureau of Mines (USBM) and U.S. Geological Survey (USGS) were used for information relative to domestic explosive consumption.

## 3. Results

### 3.1. Blasting injuries in surface mining

Forty-five fatal injuries were caused by explosives in surface mines between 1978 and 1998. Coal mines accounted for 19 (42.2%) of the fatalities; metal/nonmetal

accounted for 26 (57.8%). A total of 367 nonfatal injuries occurred during the same period, averaging about 17.5 injuries per year. Coal mines accounted for 167 (45.5%) of the injuries; metal/nonmetal 200 (54.5%). Table 2 and Fig. 1 show the annual distribution of fatal and nonfatal injuries for surface blasting in the coal and metal/nonmetal sectors. During the 21-year period from 1978 to 1998, the mean annual injuries (fatal and nonfatal) for coal mines was 8.86 (95% CI: 6.38–11.33), and for metal/nonmetal mines it was 10.76 (95% CI: 8.39–13.14).

The annual injuries for the 10-year period from 1979 to 1988 (Period-A) were compared with the following 10-year period from 1989 to 1998 (Period-B) using GraphPad Software (2002)<sup>1</sup> online calculator for t-test. The purpose was to examine if there was any reduction in the annual injuries during the later period.

The mean annual injuries for Period-A in the coal sector was 10.90 (95% CI: 7.77–14.14), and 5.80 (95% CI: 2.71–8.89) for the Period-B. The null hypothesis is based on the premise that there is no difference in the annual injuries between these two 10-year periods. The results of unpaired t-test for these two periods (DF = 18) are:  $p = 0.0190$ ,  $t = 2.5770$ , and mean of (Period-A minus Period-B) = 5.10 (95% CI: 0.94–9.26). Therefore, the null hypothesis is rejected. The analysis indicates a statistically significant decrease in the annual injuries during Period-B compared to Period-A.

A similar unpaired t-test analysis was done for the surface metal/nonmetal mines (i.e., the mean annual injuries during Period-A in metal/nonmetal sector was 11.00 [95% CI: 7.11–14.89] and 9.30 [95% CI: 6.84–11.76] for Period-B). The results of unpaired t-test for these two periods (DF = 18) are:  $p = 0.4141$ ,  $t = 0.8361$ , and mean of (Period-A minus Period-B) = 1.70 (95% CI: –2.57–5.97). The null hypothesis cannot be rejected. The resultant analysis does

<sup>1</sup> Use of brand names is for informational purposes only and does not imply endorsement by NIOSH.

not support any significant difference in the annual injuries during these two periods.

Table 3 illustrates the contribution of flyrock and lack of blast area security in surface mine blasting. Out of 412 blasting injuries (coal and metal/nonmetal), flyrock and lack of blast area security accounted for 281 (68.2%) injuries.

MSHA reported 10 fatal injuries due to flyrock and lack of blast area security in surface coal and metal/nonmetal mines from 1990 to 1999. Appendix A provides brief case study information about all of these fatalities.

### 3.2. Lessons learned from the fatal injuries

The energy released by an explosive charge in a borehole crushes the rock in the immediate vicinity of the borehole, fractures the rock beyond the crushed zone, generates seismic waves, creates airblast, and displaces the broken rock. Any mismatch between the distribution of the explosive energy, geomechanical strength of the surrounding rock mass, and confinement creates a potential for flyrock. Flyrock originates from the vertical highwall faces and also from the bench tops.

Although the circumstances of each incident varied, some important similarities were observed. Deficiency or lack of attention to personal, task, or environmental factors has the potential to cause injury. Fig. 2 provides a list of factors that play a role in successful blasting.

#### 3.2.1. Personal factors

The personal factors include education, job training, experience on the job, experience on a related job, prior injury history, visual perception, overwork, load and blast in a hurry, and work-stress, among others. However, education, job training, and experience play vital roles. In case study 8, the victim had three days mining experience and very little blast-hazard recognition training. This employee placed himself and the visitor in harms way due to lack of knowledge.

A blaster should not be in a hurry or take any short cuts. Taking short cuts or avoiding safe operating procedures can result in serious injuries and often death. Case study 2 shows that the blaster took a shortcut and went underneath a truck to detonate the blast. After a misfire, the blaster

decided to detonate the shot from a closer distance. A truck should not be considered a blasting shelter.

#### 3.2.2. Task factors

Rock blasting necessitates an excellent coordination of a series of tasks. Some of the tasks are performed by the blaster, while others are performed by the blasting crew under the supervision of the blaster. Several tasks are also performed by crews not related to blasting. The blaster should coordinate loading and firing activities with the mine foreman to ensure safety and efficiency. Failure to properly coordinate the tasks can result in serious injury or death. The list of tasks includes examination of the driller's log, inspection of the highwall, and review of laser profiling data, if any. The boreholes are examined for spacing, burden, inclination, and general layout. Case study 1 emphasizes the importance of these tasks. The next task is clearing the blast site before priming, loading, and stemming the boreholes. Once the blastholes are loaded and ready, employees should be removed from the blast area or be inside a blasting shelter. Case studies 2, 4, 6, and 9 indicate the importance of using blasting shelters. These fatal accidents could have been prevented by using blasting shelters.

Guards should be posted at the entrance to all access roads leading to the blast area. In case study 5, an access road leading to the blast area was not guarded and an area resident inadvertently entered the blast area. This was a preventable accident. Depending on the local conditions, there may be additional requirements. From the case studies, it was apparent that poor implementation or coordination of tasks can cause a fatality.

#### 3.2.3. Environmental factors

The mining environment is often very harsh. In addition to noise, smoke, dust, and uneven ground it presents numerous other environmental hazards. Movement of large equipment such as draglines, shovels, dumpers, dozers, drills, and service vehicles create distractions. Often the blaster's visibility is impeded due to large piles of overburden, dirt, or blasted material. Our study indicates that on several occasions, the blaster could not see the blast area from the firing station and that resulted in fatal injuries. An important environmental factor, often overlooked, is geo-

Table 3  
Trends in flyrock and lack of blast area security injuries in surface mining, 1978–98

| Activity or cause           | Fatal and nonfatal injuries |           |           |           |           |          | Total      |
|-----------------------------|-----------------------------|-----------|-----------|-----------|-----------|----------|------------|
|                             | 1978–81                     | 1982–85   | 1986–89   | 1990–93   | 1994–97   | 1998     |            |
| Lack of blast area security | 51                          | 28        | 43        | 25        | 17        | 3        | 167        |
| Flyrock                     | 26                          | 22        | 29        | 24        | 10        | 3        | 114        |
| Total                       | 77(61.1%) <sup>a</sup>      | 50(70.4%) | 72(77.4%) | 49(74.2%) | 27(58.7%) | 6(60.0%) | 281(68.2%) |

Source: Verakis and Lobb (2001).

<sup>a</sup> The numbers within the parenthesis indicate the flyrock and lack of blast area security injuries as a percentage of injuries reported in the Table 2 for the corresponding 4-year period.

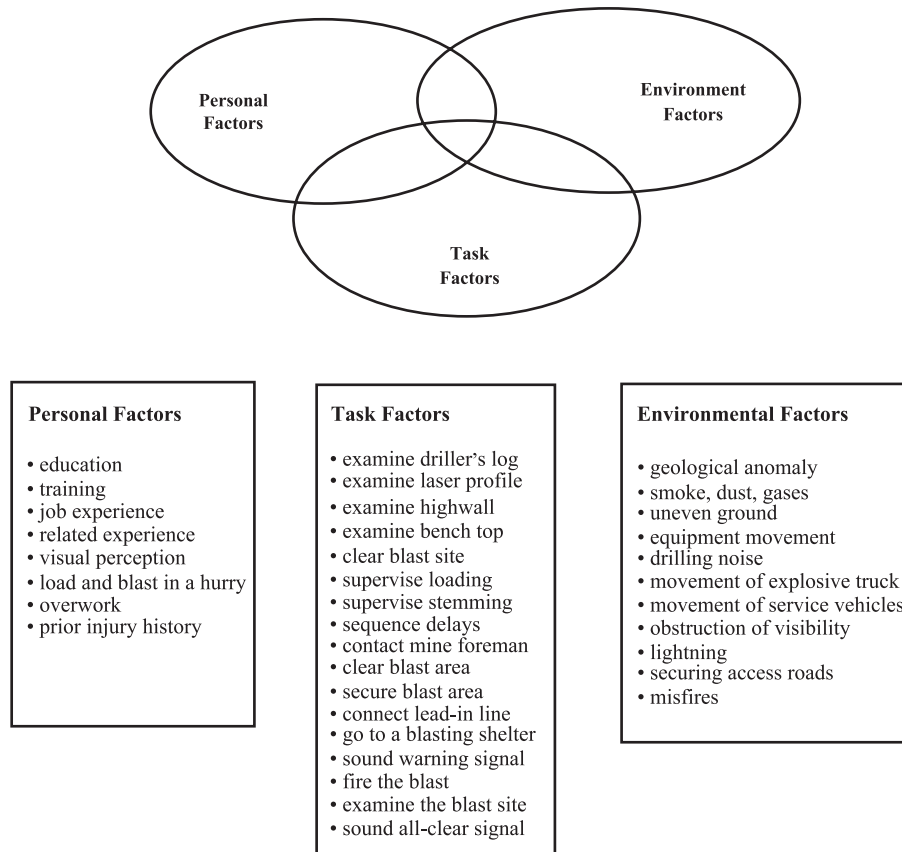


Fig. 2. List of factors involved in blasting.

logical anomalies. Case studies 3, 7, and 10 illustrate the role of geological anomaly in causing flyrock injury.

#### 4. Discussion

During the 10-year period from 1989 to 1998 a reduction in fatal and nonfatal blasting injuries in surface coal mines was observed compared to the previous 10-year period. However, in the surface metal/nonmetal mining sector such reduction was not observed.

The accident data indicate that careless or improper blasting often caused fatal injuries. The injury prevention approach is invariably multifaceted. This includes interventions conducted through training and education, engineering controls, and administrative and regulatory guidance.

##### 4.1. Behavioral/educational interventions

Blaster training and education programs are considered effective by many professionals. In addition to initial training, a typical blaster attends refresher training at regular intervals. 30 CFR, Part 955 mandates blaster training to address safety issues related to storage, transportation, and use of explosive products. The course also focuses on blast design for different types of rocks commonly encountered in

mining operations. In addition, the training course provides information relative to the regulatory requirements of explosives and blasting.

Several mining and blasting companies have instituted training programs for their employees. International Society of Explosives Engineers (ISEE) is in the process of completing several training modules for blasters. Modules for level one training are currently available and modules for level two and three will be available soon. A quality training program should address aspects of modern blasting technology and explosive safety issues.

##### 4.2. Administrative/regulatory interventions

Federal and state regulatory agencies have imposed strict requirements related to flyrock and blast area security issues. 30 CFR Part 56.6000 defines "Blast Area" as the area in which concussion (shock wave), flying material, or gases from an explosion may cause injury to persons. The CFR also states that the blast area shall be determined by considering the following factors:

- Geology of material to be blasted
- Blast pattern
- Burden, depth, diameter, and angle of the holes
- Blasting experience of the mine personnel

- Delay systems, powder factor, and pounds per delay
- Type and amount of explosive material, and
- Type and amount of stemming

30 CFR Part 77.1303 requires that ample warning shall be given before blasts are fired, and all persons shall be cleared and removed from the blast area unless suitable blasting shelters are provided to protect persons endangered by concussion or flyrock from blasting.

30 CFR Part 817.67 (c) requires that flyrock traveling in the air or along the ground shall not be cast from the blasting site:

- More than one-half the distance to the nearest dwelling or other occupied structure,
- Beyond the area of control, or
- Beyond the permit boundary.

Mining and blasting companies have instituted rigorous policies for flyrock control and blast area security.

#### 4.3. Engineering interventions

Favreau and Favreau (2002), Preece and Chung (2001; 2002), Dare-Bryan, Wade and Randall (2001), and Katsabanis and Liu (1997) have used numerical simulation techniques to predict blast results by computing the interaction of rock and explosive. A blaster may be able to improve the design of a blast by using such simulation techniques. Proprietary software developed by explosive manufacturers is often available for consultation. Most of these design codes are capable of addressing variability of the rock type, depth, diameter, delay, and spacing of boreholes. In addition, some software programs will predict the trajectory of the muckpile. Sensitivity analysis and model studies, using computer simulation, should be pursued prior to field blasting. This would help the blaster examine the expected outcomes and modify loading parameters, if necessary.

Engineering interventions are well understood by the blasting community and work well. Dick, Fletcher, and D'Andrea (1983), D'Andrea and Bennett (1984), and Fletcher and D'Andrea (1986) advocated the use of portable blasting shelters. The shelter is cylindrical in shape and constructed of heavy gauge sheet metal and able to withstand potential impact from flyrock. This portable shelter is mounted on wheels or skids for ease of towing from one blast area to another. The blaster enters the shelter and closes the door prior to firing the shot.

## 5. Conclusions

Blasting releases a tremendous amount of energy for fragmenting and displacing rocks within a very short time. The blast should be designed so that the energy released by detonation performs useful work. Any imbalance

between the distribution of the explosive energy, geomechanical strength of the surrounding rock mass, and confinement creates a potential hazardous condition by channeling the energy through the path of least resistance. Such imbalance can propel flyrock beyond the blast area and create a potential for serious injuries and fatalities. Case studies listed in Appendix A underscore this issue. Blasters should follow procedures required by local, state, and federal statutes to guard against catastrophic consequences.

The principal factors attributed to the fatalities were personal, task, and environmental. Intervention programs in the realm of behavioral/educational, administrative/regulatory, and engineering merit serious attention. During the 10-year period from 1989 to 1998, a reduction in fatal and nonfatal blasting injuries in surface coal mines was observed compared to the previous 10-year period (1979–1988). However, in the surface metal/nonmetal mining sector such reduction was not observed.

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## Appendix A. Fatality case studies related to flyrock and/or blast area security (1990–1999)

The incidents are arranged chronologically for coal mines followed by nonmetal mines.

**Case 1**—Coal Mine, Walker County, AL. On September 22, 1990, flyrock projected from a surface coal mine blast fatally injured the owner of a logging company (MSHA, 1990c). He was in the process of preparing access roads for future logging operations and was outside the mine property.

Fifty-four holes, in six rows, 22.9-cm diameter, 12.2-m deep, on a 5.5- by 5.5-m pattern were loaded with emulsion explosive. Each hole contained about 392 kg of explosives. The stemming length was 3.0 m. The pit area was cleared and the shot was fired. The blast projected flyrock about 275 m and fatally injured the victim. Several large boulders, scattered over an area near the accident site, were noticed. The MSHA investigation report indicated that a blown out shot caused the flyrock. This incident emphasizes the importance of paying attention to task factors such as blast design, highwall inspection, determination of the bounds of the blast area, and blast area security.

**Case 2**—Coal Mine, Mingo County, WV. On February 1, 1992, a blaster was fatally injured in a surface coal mine by a 43- by 89- by 22-cm flyrock (MSHA, 1992). Eighty boreholes, 22.9-cm in diameter, on a 5.5- by 5.5-m pattern were loaded with 16,064 kg of explosives. The stemming length was 3.0 m. Sixty-two holes were 9.1m deep and each hole was loaded with 212.3 kg of bulk ANFO. Eighteen holes were 6.1m deep and each was loaded with 159.2 kg of bulk ANFO. Drill cuttings were used for stemming.

On the day of this incident, the blaster and helper loaded 80 holes. Upon clearing the blast area and securing access roads, the shot was fired from a distance of 457 m. A misfire was noticed and after 15 minutes, the blaster returned to the blast site, examined the shot area, and reconnected the lead-in line in preparation of firing the remaining holes. The blaster positioned himself under a Ford 9000, 2-1/2-ton truck and fired the shot from a distance of 229 m. Upon firing the shot, the blaster was fatally injured by flyrock. He was treated for collapsed lungs, multiple rib fractures, fractured mandible, dislocated left shoulder, and serious head injuries.

The MSHA investigation report indicated that the blaster was within the limits of the blast area and did not use a proper blasting shelter. This tragedy could have been avoided by using a proper blasting shelter. The space under a truck should not be used as a blasting shelter. This incident underscores the importance of personal and task factors.

**Case 3**—Coal Mine, Campbell County, TN. On June 4, 1993, a 16-year-old passenger in a car driven by his parent on interstate 75 (I-75), was fatally injured by flyrock originating from an overburden blast in a nearby coal mine (Shea & Clark, 1998). The closest blasthole was within 22.9

m of the Right of Way (RoW) and 68.6 m from the I-75 pavement.

Twenty-eight blastholes, in four rows, on a 5.5- by 5.5-m pattern, 18.4-cm diameter, were loaded with ANFO. Each hole contained 259.9 kg of explosive and was stemmed with 3.4 m of drill cuttings. The length of explosive column in each hole was about 9.8 m. Unlike previous blasts, explosive charges were not decked during this blast.

The investigation report (Shea & Clark, 1998) indicated that this blast was not designed according to the specifications approved in the permit document. Instead of decking explosive charges in two columns and priming separately, the entire charge was loaded in one column. Hole diameter and blast pattern used were different from the approved plan. The I-75 traffic was not monitored. The presence of a 2.4-m thick layer of clay on the top of the sandstone overburden was considered a contributory factor.

The causative factors were single decking of holes instead of double decking on separate delays and a change in the geology of the overburden. Preventive measures should include paying close attention to drillers' log and watching for any abrupt changes in the geology or rock structure. Blast design parameters should not be changed without a critical review of its impact. This incident underscores the importance of task and environmental factors. In addition, the I-75 traffic should have been temporarily stopped immediately prior to blasting.

**Case 4**—Coal Mine, Greene County, IN. On April 25, 1994, a 34-year-old driller/loader was fatally injured by flyrock in a surface coal mine (MSHA, 1994a). Coal was mined from a 1.5-m thick seam having a shale parting at the middle. One hundred and seventeen holes, 17.1-cm diameter, 3.4-m deep were drilled on a 3.4- by 3.4-m pattern. Each hole was backfilled with about 0.3 m of dirt and loaded with 19.4 kg of emulsion-type explosive. The length of stemming varied from 2.3 to 2.4 m. There were nine rows with 13 holes per row. Some of the holes contained water.

The blasting crew notified the superintendent of an impending blast and cleared other employees from the pit area. The victim and another employee working under the direction of the blaster were about 72 m from the blast area. Upon firing the blast, the victim was fatally injured by flyrock.

The MSHA investigation report indicated that the accident was caused by failure to use an adequate blasting shelter. This incident emphasizes the importance of using proper blasting shelters for employees whose presence is required in the blast area. This incident focuses attention to personal and task factors.

**Case 5**—Coal Mine, Pike County, KY. On February 15, 1999, a 55-year-old area resident rode an all-terrain vehicle (ATV) from his residence to an access trail leading to the mine site (MSHA, 1999a). He parked his ATV about 30.5 m from the edge of the blast site and started walking toward the blast site. Shortly after he started walking, a blast was detonated. Later, his body was found close to the perimeter

of the blast site. Mining was conducted on privately-owned land, including land owned by the victim.

A total of 212 holes, 17.1-cm diameter, loaded with 5,900 kg of explosive, were detonated. Of these, 164 holes were 4.0 m deep, and 48 holes were 7.0 m deep. The blastholes were drilled on a 4.0- by 4.6-m pattern. The blast area and the access trail leading to the blast area were examined about five minutes before the blast. The MSHA investigation report indicated that guards were not posted at the access trail, and the blaster did not have a clear view of the access trail from the firing station. A Ford F-250 pickup truck was equipped with two electro-mechanical horns. However, on the day of the incident only the low-pitch horn was operational and the high-pitch horn was found to be disconnected. The access trail was in a valley, and it was probably difficult for the victim to hear the signal.

This incident underscores the need for effective blast area security and focuses attention primarily on the task factors.

**Case 6**—Nonmetal mine, Caldwell County, KY. On July 5, 1990, a blaster was fatally injured by flyrock while standing in the open about 154 m from the blast site. The blaster was standing on the highwall about 61 m above the blastholes. Flyrock measuring 23-by18-by13-cm and weighing about 6.4 kg, traveled over the highwall and injured the blaster (MSHA, 1990a).

On the day of this incident, blasters were assigned to blast a toe round. The toe round consisted of 23 holes ranging in depth from 0.9 to 1.5 m. The holes were loaded with 6.4 cm diameter packaged explosive product. A total of 79.8 kg of explosive, averaging 3.4 kg per hole, was used.

This incident could have been prevented by using a blasting shelter and emphasized the importance of task factors.

**Case 7**—Nonmetal Mine, Livingston County, IL. On July 11, 1990, flyrock from a limestone quarry traveled about 284 m and fatally injured a resident who was mowing grass on his property (MSHA, 1990b).

On the day of this incident, 36 holes in three rows, 12 holes per row, were loaded with 1,160 kg of ANFO. The holes were 12.1-cm in diameter and 6.6-m deep. The spacing and burden were 4.1m and 2.7m, respectively. The upper 1.5m of each hole was stemmed with drill cuttings and crushed stone. One of the holes near the center of the front row was found to be overloaded.

The MSHA investigation report indicated that an overloaded hole in the front row was a contributory factor for this incident. Overloading creates an imbalance between the available explosive energy and the rock resistance. Such situations can create problems in the front row of blastholes. A blaster should observe the rise of explosive column while loading a borehole to control loss of powder in voids, mud seams, or crevices (Fletcher & D'Andrea, 1986). If a void is encountered, it should be filled with inert material (Dick et al., 1983). This incident focuses attention to task factors.

**Case 8**—Nonmetal Mine, Luna County, NM. On October 12, 1990, a visitor sustained severe injuries and a drill/blast helper was fatally injured by flyrock in a surface silica flux mine (MSHA, 1990d). The visitor was hospitalized for broken ribs and internal injuries and the drill/blast helper was pronounced dead. The drill/blast helper had three days mining experience and had little training in blast hazard recognition. The visitor wanted to take a photograph of the blast.

The ore was mined by drilling and blasting from shallow multiple benches. The mining company used a blasting contractor for loading and firing the shots. The blast round consisted of 49 holes, 7.6-cm diameter, 3.7-m deep, on a 1.8-m spacing. Some of the holes were stemmed with 0.6 m of drill cuttings. Several holes were completely filled with ANFO. A detonating cord trunk line was used to tie each hole without any firing delay. The trunk line was tied to a cap and fuse assembly.

The visitor and the drill/blast helper were about 46 m from the edge of the blast. Upon firing the shot, the drill/blast helper was fatally struck on the back side of his head. The MSHA investigation report indicated that poor blasting practice (such as overcharging boreholes, lack of stemming, and absence of delays) was exhibited during this shot. The employee was not properly trained and was too close to the blast. This accident emphasizes the significance of personal and task factors such as hazard recognition training, proper blast design, and deployment of blasting shelters.

**Case 9**—Nonmetal Mine, Madison County, IL. On May 23, 1994, a crane operator was fatally injured by flyrock that struck him in the back (MSHA, 1994b). He was 21 years old and had 1–1/2 months mining experience at this mine. Forty-one holes, 8.9 cm diameter, 3.7 m deep, were loaded with ANFO. The bench height was 3.4 m. The length of stemming was about 0.9 m and crushed limestone was used for stemming. The stemmed holes were covered with blasting mats of 0.9- by 0.9-m size. Pails containing crushed stone were placed over the mats.

On the day of this incident, the crane operator helped in stemming the holes, and placing blasting mats over the holes. The victim and the blaster moved to a top bench behind the blast and were standing in the open about 37 m from the nearest blasthole. Upon initiation of the blast, one of the holes threw flyrock toward the victim. The MSHA investigation indicated that the crane operator did not use a blasting shelter. This incident emphasizes the importance of personal and task factors.

**Case 10**—Nonmetal Mine, Lancaster County, PA. On December 21, 1999, a 32-year-old equipment operator was in a pickup truck guarding an access road to the blast site (MSHA, 1999b). The pickup truck was about 244 m from the blast site. Flyrock entered the cab through the windshield and fatally struck the victim. The victim had seven years mining experience as an equipment operator at this mine.

The highwall face was about 15.2 m high and the depth of holes ranged between 14.9 and 16.5 m. The blast round consisted of 22 holes drilled on a 4.9- by 4.9-m pattern. Approximately 4,352 kg of explosives were used in this round and the length of stemming varied from 2.7 to 11.0 m. The weight of explosive used in each blasthole was not recorded. Some of the holes were slanted up to 25° toward the highwall. This was done to compensate for irregularities in the highwall face. Drill records indicated that several blastholes were broken and contained voids. The MSHA investigation indicated that at least one of the blastholes blew out causing flyrock. This incident emphasizes several issues, such as, blast design, loading of voids, burden, confinement, and record keeping, which are task factors.

**Dr. T.S. Bajpayee** is a mining engineer in the Disaster Prevention and Response Branch of the Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health. He is involved in research related to the safety issues of explosives and blasting agents at this laboratory since 1982. Prior to 1982 he worked in the mining industry in production and safety. He is currently working on flyrock hazards in blasting. His research experiences includes hazard classification of explosives and explosive actuated devices. After completing B.S. in Mine Engineering, he conducted graduate study and research leading to Ph.D. in Mine Engineering. He has an integrated work experience, including production, consulting and research. He is also a registered professional engineer in the state of Pennsylvania. He has authored several publications. He is a member of the International Society of Explosives Engineers.

**Tim Rehak** is a general engineer for the National Institute for Occupational Safety and Health (NIOSH), National Personnel Protective Technology Laboratory (NPPTL), Policy and Standards Branch. Mr. Rehak is currently responsible for writing/developing national certification requirements for self-contained closed-circuit breathing apparatus and powered air purifying respirators. Prior to this, Mr. Rehak worked as a physical scientist and a general engineer for NIOSH's Pittsburgh Research Laboratory in the Disaster Prevention and Response Branch with both the Explosives and Life Support Groups. In the Explosives Group, he was the Principal Investigator for research projects titled: Investigation of Flyrock Injuries and Fatalities; Toxic Fumes Field Studies; and Investigation of Carbon Monoxide Migration from Blasting Operations. With the Life Support Group, he participated in studies related to: heart rate/oxygen cost of mine escapes; long-term field evaluation of self-contained self-rescuers (SCSRs); and improvements for a new, third-generation SCSR. Mr. Rehak has a BS in Civil Engineering from the University of Pittsburgh and is a Registered Professional Engineer in Pennsylvania.

**Dr. Gary L. Mowrey** is an electrical engineer in the Mining Injury Prevention Branch of the Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health. He is involved in several work safety-related research projects including two NORA projects (Project Leader: Lockout/tagout, Jammed, and Moving Machinery Controls; Co-Project Leader: Evaluating Roadway Construction Work Zone Interventions). Other projects include Flyrock (to investigate flyrock problems and accidents, determine causes, and recommend solutions), and System Safety (to develop safety guidelines for computer-controlled machinery). He is also involved in investigating utilizing ground-penetrating radar for assessing mine seal and roof strata integrity. He previous worked on research and development of various types of coal-rock interface detection systems for mining machines for the U.S. Bureau of Mines since 1986. Prior to this Dr. Mowrey was a geophysical well logging engineer for Schlumberger Ltd. (1969–1972, Ghana and Nigeria) and later became a borehole mechanics research engineer in the drilling section for Shell Development (1980–1985, Houston, TX). He received a BSEE degree (1969), an MS (1977) and a Ph.D. (1980) degree in Mining Engineering, all from The Pennsylvania State University, specializing in geomechanics and microseismic research.

**Dave Ingram** is employed as a Research Geologist for the National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory. Mr. Ingram has been affiliated with Mining Research for 21 years. His research efforts have focused on identifying geological hazardous mine roof conditions, measuring in-situ mine roof stresses, identifying the overburden failure and ground water characteristics induced by longwall mining, and injuries and fatalities associated with blast area security and flyrock. Currently, Mr. Ingram is involved with research focusing on the potential hazards associated with water well drilling.