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EVALUATION OF SURFACE STORAGE FACILITIES FOR EXPLOSIVES, BLASTING AGENTS AND OTHER EXPLOSIVE MATERIALS

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16. Abstract (Limit: 200 words)

The purpose of this study was to increase the safety of explosive storage. This was accomplished by (1) review of the histories of recent and past magazine explosions, (2) observation of present explosive storage conditions and practices, (3) examination of existing Federal regulations on explosive storage, and (4) recommendations for safety improvements and revision and clarification (if necessary) of governmental regulations. A recent increase in magazine explosion frequency must be attributed to a large increase in deliberate explosions; fires of various origins account for the remaining explosions of the past decade. During 1884-1926 several lightning-generated explosions occurred in nonmetal magazines. It appears that the contents of a well-constructed metal magazine are immune to direct lightning strikes, regardless of whether the magazine is grounded or not. Grounding a metal magazine cannot be harmful, but it may well be superfluous. Magazines were observed at 34 widely separated mines and storage problems were discussed with the personnel. In general, storage conditions and practices were found to be satisfactory. Usually, only small quantities of explosives were stored on mine property because most explosives are brought in by suppliers when needed. Mine Safety and Health Administration and Bureau of Alcohol, Tobacco and Firearms standards on explosive storage appear to cover safety aspects adequately. However, certain revisions are recommended to clarify some of the standards and to reduce inconsistencies in their enforcement.

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Mining research

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FOREWORD

This report was prepared by Management Science Associates under USBM contract number J0318071. The contract was initiated under the Health and Safety Technology Program. It was administered under the technical direction of the Bureau of Mines, U.S. Department of the Interior with Richard Mainiero acting as Technical Project Officer. William R. Mundorf was the Contract Administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period September 22, 1981 to June 1, 1983. This report was submitted by the authors on June 1, 1983.

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Several individuals who were neither employed by nor consultants to Management Science Associates (MSA) contributed to the success of this project. It is particularly gratifying to acknowledge the assistance given us by Dr. Richard Mainiero, the Bureau of Mines Technical Project Officer. Messrs. C. E. Reich and R. L. Fischer of MSHA's Technical Support Staff provided helpful discussions. Messrs. T. C. Lukins, MSHA's Western District Manager and Douglas Boyd, BOM Liaison at HSAC provided us with data on mine types and mine locations. Messrs. A. B. Oppermann and R.N. Prescott of IME presented their views on several aspects of explosive storage and furnished us with pertinent information.

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1.0 SUMMARY

The purpose of the present study is to increase the safety of explosive storage. This was accomplished by:

- review of the histories of recent and past magazine explosions to define causes and trends;
- observation of present-day explosive storage conditions and practices at a variety of active mines;
- examination of existing Federal regulations pertaining to explosive storage to determine whether they address all conceivable safety problems, whether they contain redundant or obsolete standards, and whether their intent is clearly stated;
- recommendations for safety improvements and for revision and clarification (if necessary) of governmental regulations.

Magazine explosions are rare. In the past decade, there were roughly 10, but only about seven per decade for the period 1884 to 1926. This apparent increase in magazine explosion frequency must be attributed to a large increase in deliberate (criminal or malicious mischief) explosions. During the 1970-1980 decade there were six such explosions while over the forty-plus years of 1884-1926, there were only three.

Fires of various origins account for the remaining four explosions of the past decade. Fire was also a major hazard in the 1884-1926 period, but so was lightning. It is noteworthy that all these lightning-generated explosions occurred in non-metal magazines.

The potential hazards created by a lightning stroke upon an explosive magazine were examined in considerable detail. It is concluded that the contents of a well-constructed, metal magazine are immune to direct lightning strikes, regardless of whether the magazine is grounded or not-grounded.* Grounding a metal magazine cannot be harmful, but it may well be superfluous. For non-metal magazines, statistical analysis suggests that there is

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*Provided that the magazines do not contain electrical lighting. Very few present-day magazines have electrical lighting.

a high probability of one lightning-generated explosion of a <u>non-metal</u> magazine in a <u>15-year</u> period. Effective lightning-protection systems should minimize this frequency, but in view of the already low frequency, the cost of implementing an effective system does not appear to be justified except in special cases.

It should be emphasized that fires initiated by nearby lightning strikes did result in the explosion of two magazines in the last 10 years. For this and other reasons, it is imperative to keep areas around magazines clear of combustible materials. Combustible fuel/air mixtures which may develop in unventilated AN-FO drop trailers during hot weather can also be potential fire hazards.

Magazines were observed at 34 widely separated mines and storage problems were discussed with personnel at these mines. In general, storage conditions and practices were found to be satisfactory and in compliance with MSHA regulations. Usually only small quantities of explosives are stored on mine property since most explosives are brought in by suppliers when needed.

MSHA and BATF standards on explosive storage were examined from the point of view of adequacy (with regard to safety) and clarity (with regard to complaints by the mining community about inconsistency of enforcement of these standards). Safety problems, with the possible exception of lightning hazards, were found to be adequately covered. Standards that need clarification are listed and recommendations are made for removing vagaries, redundancy or inconsistency from these standards.

2.0 INTRODUCTION

There are numerous reasons why storage of explosives should be an inherently safe operation. Modern explosives are chemically stable under normal storage conditions. Indeed many of the modern explosives (water gels, AN-FO) tend to become less sensitive upon prolonged storage. Thus in the absence of appropriate external stimuli, explosives can be stored safely for very long periods. To eliminate potentially hazardous external stimuli, governmental agencies, in cooperation with the explosives industry, have developed a set of standards for the safe storage of explosives. To reduce risks even further, there are also legal requirements for minimum separation distances between storage magazines in order to prevent sympathetic explosions. Ideally then, there should be no explosions of explosive storage magazines. Unfortunately, such is not the case though magazine explosions are quite rare. By their very nature, explosive magazines can be foci for the concentration of large amounts of explosives, thus these infrequent explosions have the potential of producing major disasters. Consequently, it is the objective of the present study to make explosive storage even safer than it now is. This is to be accomplished by:

- examining histories of previous magazine explosions to determine trends and causes;
- visiting a sufficient number of active mines and viewing their explosive storage facilities in order to get an overview of current storage conditions and practices;
- reviewing existing MSHA regulations on explosive storage from the point of view of pertinence, clarity, and acceptability to industry;
- recommending viable revisions to these regulations if revisions appear appropriate.

The order in which the major results of our study are presented is:

Section 3.0: Mine Visits - type of mine, location, type and amount of explosives stored, storage conditions, comments from mine personnel, ventilation

Section 4.0: Magazine Explosions - present, past, explosives involved, causes and trends

Section 5.0: Established and Potential Hazards - break-in for theft or mischief, bullet impact, lightning, nearby power lines, improper siting of magazines, AN-FO fumes

Section 6.0: Comparison of Existing Standards and Recommendations - MSHA, BATF, OSHA, IME, and the various states

Section 7.0: Conclusions

Section 8.0: Recommendations

3.0 MINE VISITS

Actual observation of conditions and practices in the storage of explosives in the mining industry necessitates visits to operating mines. Additionally, such visits can and do provide the opportunity to obtain comments from the mining community as to their views on how storage practices can be improved. As will be shown later, most of these comments concerned government regulations and especially enforcement of such regulations.

3.1 Selection of Mines for Visits

The following tabulation (obtained from HSAC, Denver) shows that the number of active mines, as of the end of 1981, is large:

Operation	Number of Mines
Surface coal	3,754
Underground coal	2,586
Surface metal	655
Underground metal	546
Non-metal (surface and underground)	1,201
Quarries	2,927
TOTAL	11,669

Since only a very small fraction of this large total could be visited, mines selected for visits had to be picked with care. The criteria for selection were:

1. use of explosives (e.g., many underground coal mines do not use explosives),
2. representative of the major commodities mined with explosives,
3. wide geographic distribution,
4. near major MSHA offices.

The first of the above criteria is self-explanatory. The second criterion ensures that most of the visits will be to mines of the type that use a large proportion of the annual explosive consumption; e.g., coal mines. Visits to mines within a narrrow geographic area could result in acquisition of false impressions of explosive storage conditions for the entire country. Thus, at least some of the mines visited should be widely separated - criterion three. It was expected (and subsequently confirmed) that valuable information on explosive storage could be obtained from discussions with MSHA personnel in various parts of the country. This was the reason for criterion four.

3.2 Mines Visited and Personnel Contacted

Eventually, 34 mines were visited in ten states. Of the mines approached for permission to visit (in addition to 34 mines visited) five refused permission. Four of these five were coal mines in the Western Pennsylvania and West Virginia areas.

Table 1 shows the locations and the types of mines visited. Table 2 shows that most of our visits were to medium-to-large mining operations, because it was felt that the chances of fruitful discussions with mine personnel were more favorable at these operations than at small mines where the workers are too busy with their daily routines to be able to devote much time to a frequently unwelcome visitor.

The various MSHA offices visited are shown in Table 3. In general, discussions with MSHA personnel concerned existing regulations on explosive storage and their enforcement, as well as potential hazards and accidental explosions of explosive magazines.

Shortly after the start of this project, MSA was contacted by members of IME (Institute of Makers of Explosives) with offers of assistance. This led to several helpful meetings with IME members and with technical personnel of explosive manufacturers. The people contacted and their affiliations are shown in Table 4.

3.3 Information Obtained During Mine Visits

Because mine visits were expected to be (and actually were) rather brief, it was mandatory to gather information effectively and rapidly. To do this it was decided to use a prepared question list which ensured that none of the important items of information sought were omitted, and it also provided space to record succinctly the information obtained. The question list used is shown in Appendix A. Generally, a visit proceeded somewhat as follows:

TABLE 1.-LOCATION AND TYPE OF MINE VISITED

	AL	AZ	CA	CO	IN	KY	MN	OH	PA	WV	TOTALS
Surface Coal	2				2	1		2	1	1(b)	9
Underground Coal	2					2			(b)		4
Surface Cu		2(a)									2
Underground Cu		2									2
Taconite							6				6
Quarries	2	1	1	3							7
Underground Ur				1							1
Underground AG/Au		1		1							2
Surface Ag/Au		1									1
Mo				(a)							
TOTALS	6	7	1	5	2	3	6	2	1	1	34

(a) One mine refused permission for a visit

(b) Two mines refused permission for a visit

TABLE 2.-Work Force in Mines Visited*

No. of employees	≤10	10-30	30-60	60-120	120-200	200-400	400-600	600-800	800-2000	>2000
Surface Coal			2	2	2	2	1			
Underground Coal			1	1		2				
Surface Cu						1		1		
Underground Cu								1	1	
Taconite							2	1	2	1
Quarries		6 (a)								
Underground Ur					1					
Underground Ag/Au	2									
Surface Ag/Au			1							

*Numbers in Table are the number of mines of the indicated work force

(a) No data for one quarry

TABLE 3.-MSHA OFFICES VISITED

	Metal/Non-metal	Coal
Pittsburgh*	X	X
Birmingham	X	-
Denver**	X	-
Alameda	X	-
Duluth	X	-
Phoenix	X	-
Morgantown	-	X
Madisonville	-	X

* District offices & Tech Support

** The district office, HSAC, Tech. Support

TABLE 4.-VISITS TO IME AND EXPLOSIVE SUPPLIERS

Person	Affiliation	Number of Visits
Oppermann	IME & Dupont	3
Prescott	IME & Austin	1
Boddorff	IME	1
Rucker	Dupont	1
Angotti	Hercules	1
Bean	Apache	1
Skully	Austin	1
Baxter	Baxter Drilling Co. (a)	1

(a) Explosive Distributor

1. Fill-in most of the question list.

2. Solicit discussion on storage safety, storage regulations, storage accidents, etc.

3. Inspect magazines and take photos if permitted.

4. Write-in commments on the condition of the magazines observed in the appropriate spaces of the question list.

At the larger mines, the person interviewed was usually the drilling and blasting foreman and occasionally the mine superintendent or safety director. At the small mines, it was usually the mine owner (or part owner) who combined within himself the roles of drilling and blasting foreman, safety director, and almost everything else.

The information obtained is presented as follows:

- General type and amount of explosives stored (Table 5)
- Specific type of explosives stored (Table 6)
- Explosive consumption and shot frequency (Table 7)
- Qualitative rating of storage conditions (Table 8)
- Storage of fuse lighters (Table 9)
- Magazine siting (Table 10)
- Non-metal magazines (Table 11)
- Ventilation of magazines (text)
- Comments on explosive storage from mining personnel (Appendix B).

In Table 5 (and subsequent tables), the column headings of HE, BA and Det. Cord, and BP refer to High Explosives, Blasting

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Both MSHA (CFR30 77.100 item q) and BATF (Fed. Reg. 46, Aug 7, 1981, p. 40386) use the term "explosive" generically to include high explosives, low explosives and blasting agents. To avoid confusion we have chosen to use the term high explosives to differentiate these "explosives" from blasting agents and low explosives.

Table 5.-OBSERVED EXPLOSIVE STORAGE

Operation	Mine	HE K lbs	BA K lbs	Det. Cord K ft.	Deto- nators K items†	No. of Magazines
Surface Coal	A	1	60	30	∿1	5*
Surface Coal	B	1	36	0	1.5	10*
Surface Coal	C	25	30	(a)	15	2**
Surface Coal	D	1	60	0	1	4*
Surface Coal	E	1.2	60	10	1.3	3*
Surface Coal	F	50	280	0	10	2
Surface Coal	G	1.7	240	250	2.3	4*
Surface Coal	H	4.3	120	150	3	9*
Surface Coal	I	2.3	80	10	0.3	4*
Underground Coal	J	15	0	0	10	2
Underground Coal	K	≤20	0	0	4	2
Underground Coal	L	14	0	0	20	2
Underground Coal	M	5-10	0	0	8.5	2
Surface Cu	N	∿100(c)	120(b)	(a)	∿100	2
Surface Cu	O	12	(b)	(a)	3.2	2
Underground Cu	P	∿100(c)	-	(a)	∿100	4
Underground Cu	Q	10	(b)	(a)	1	4
Underground Ur	R	∿3	20	20	15	2
Underground Ag/Au	S	∿1	∿3	0	6	2
Underground Ag/Au	T	<<1	2	0	1	2
Surface Ag/Au	U	<<1	60	0	0.2	2
Taconite	V	3	(b)	(d)	0.1	4***
Taconite	W	2	(b)	125	0.1	3
Taconite	X	2.3	2&(b)	100	0.1	7****
Taconite	Y	20	(b)	(a)	1	2
Taconite	Z	4.3	(b)	250	1.6	4
Taconite	AA	2	(b)	70	1.1	2
Quarries	AB	5(c)	(c)	0	1	2
Quarries	AC	1	(b)	0	0.7	2
Quarries	AD	1	20&(b)	0	10	2
Quarries	AE	1	2	0	2	3
Quarries	AF	6	10	0	2	2
Quarries	AG	0.4	40	0	2	2
Quarries	AH	2	40	0	2	2

(a) Included in HE storage
(b) Brought in by supplier
(c) Mostly BA stored with HE
(d) Not determined

† K ft. = 1000 ft.
K items = 1000 items

* Includes ANFO trailers and ANFO bins
** Also many day boxes
*** HE boosters & det. cord each stored in seperate magazine
**** 3 of these are very small cap magazines

Agents, Detonating Cord and Black Powder, respectively. In Table 6, EB's stand for Electric Blasting Caps and EBW's for Exploding Bridgewire Blasting Caps. Note that most mines stored little HE - 25 of 34 stored less than 10K lbs (10,000 lbs.) and most of these much less than 10K lbs. The one operation (Mine F) that stored 50K lbs. of HE used it for boostering AN-FO. Similarly, only 6 of 34 mines stored 10K or more detonators. None of the mines visited used "large" (ca. 10 gram) detonators and indeed mine personnel were not even aware of the existence of such devices. As expected, the majority of operations had only two magazines. Where more than two magazines were observed most of these were either AN-FO trailers or AN-FO bins. The data in Table 5 show that a large proportion of the explosives used in mining is brought in by the supplier as needed and is <u>not stored-on mine-property!</u>

Table 6 shows that all operations visited, except underground coal mines, store AN-FO and all stored detonators; with fuse caps definitely in the minority. Slurries were found at more mines than dynamites, and most of the slurries (again excepting underground coal) were of the blasting agent variety. Only one operation stored minor amounts of a two-component explosive.

As shown in Table 7, blasting agents constitute the bulk of the explosives consumed, with surface coal, surface copper and taconite accounting for a large proportion of the explosives used. Explosives to be kept in magazines are brought in usually once or twice a month. Shot frequency varies greatly. One underground coal mine shoots about 240 times daily, and the other underground coal mines visited fire about 60 shots/day. At the other extreme, some taconite operations shoot only once a month. Blasting in surface coal or surface copper mines is at the rate of once or twice per day. The one underground Ur mine visited shot 20 times a day. Quarries shoot at about one to four times per week.

Storage conditions are rated qualitatively in Table 8. Poor ratings were given for overloading, sloppy interiors, presence of non-explosive items (e.g., two condenser type blasting machines in a detonator magazine!) and combustible materials around the magazines. In general, the storage conditions and practices observed were adequate. Only 5 of 34 magazines were rated "bad" or worse. Two of these bad or worse ratings were given to small Ag/Au mines and the very bad rating was for a magazine at one such mine that had <u>outside contractors</u> doing the drilling and blasting. Mine management at this operation had little or no control over explosives.

TABLE 6.-TYPES OF EXPLOSIVES STORED*

	Dyna-mite	Slur-ries	Cast Boosters	Det. Cord	Delay EB's or EB's	Fuse Caps	Nonels	EBW's	DuPont Non-elec. Det.	Kinepac	AN-FO
Quarries	2	4	5	0		0	2	0	1	0	7
Taconite	1	6	6	6	5	0	4	0	0	0	5
Cu Surface	0	2	1	2	0	1	0	1	0	0	2
Cu Underground	2	1	0	2	2	0	0	0	0	1	1
Ag/Au	2	1	0	0	1	2	1	0	0	0	3
Ur	0	0	1	1	1	0	1	0	0	0	1
Coal Surface	1	0	7	8	4	0	5	0	0	0	9
Coal Underground	1	3	0	0	4	0	0	0	0	0	0

* Number of operations storing the particular item

TABLE 7.-AVERAGE MONTHLY CONSUMPTION OF EXPLOSIVES AND BLASTING SCHEDULE

	Mine	HE K lbs	BA K lbs	Det. Cord K ft.	Deto-nators K items	Explosives are Ordered	Blasting Schedule
Surface Coal	A	10	1,200	(a)	7	Once/week	2/day
Surface Coal	B	5	700	6	5	every day	6/day (c)
Surface Coal	C	2	900	100	1	Once/1.5 months	1/day
Surface Coal	D	1.4	600	120	1.5	Twice/month	2/day
Surface Coal	E	3	270	150	3	Once/week	1/day
Surface Coal	F	40 (b)	480	0	2.5	Every day	1/day (min.)
Surface Coal	G	2.4	650	200	0.7	Once/month	2/day
Surface Coal	H	2.2	200	130	2.3	Once/month	1/day
Surface Coal	I	(a)	(a)	(a)	(a)	Thrice/month	1/day
Underground Coal	J	20	0	0	8	Once/1.5 months	60/day
Underground Coal	K	30	0	0	20	Twice/month	60/day
Underground Coal	L	35	0	0	7.5	Twice/month	240/day
Underground Coal	M	5	0	0	3.3	Once/month	60/day
Surface Cu	N	2	910	(a)	0.2	Once/month	1/day
Surface Cu	O	0.5	300	3	0.5	(a)	4/week
Underground Cu	P	215(e)	-	0	250	Twice/week	6/day
Underground Cu	Q	25	0	100	10	Twice/month	1/day (d)
Underground Ur	R	(a)	(a)	(a)	(a)	Twice/month	20/day
Underground Ag/Au	S	1	4	0	(a)	Once/2 months	2/day
Underground Ag/Au	T	0.1	2	0	1	Once/month	2/day
Surface Ag/Au	U	0.1	10	0.3	(a)	Once/month	Irregular
Taconite	V	1.8	1,200	35	0.8	Once/month	2/week
Taconite	W	1	600	48	1	Once/month	3/month
Taconite	X	2	600	50	1	Twice/month	2/week
Taconite	Y	0.8	150	50	0.5	(a)	1/week
Taconite	Z	4.5	2,000	180	1.2	Twice/month	5/month
Taconite	AA	(a)	(a)	(a)	(a)	Once/month	1/week
Quarries	AB	0.5	60	0	0.5	(a)	2/week
Quarries	AC	0.4	50	0	0.4	Once/4 months	2/week
Quarries	AD	0.3	60	0	0.5	Once/month	3/week
Quarries	AE	14	35	0	0.7	Twice/week	2/week
Quarries	AF	0.7	22	0	0.7	Twice/month	4/week
Quarries	AG	0.2	40	0	0.2	Once/month	1/week
Quarries	AH	(a)	(a)	(a)	(a)	Once/month	1/month

(a) Not determined
(b) Uses dynamite boosters
(c) Several pits
(d) Many secondary shots
(e) Some BA

TABLE 8.-QUALITATIVE RATING OF OBSERVED EXPLOSIVE STORAGE

	Good	Fair	Bad	Very Bad
Surface Coal*	6	1	-	-
Underground Coal	1	2 (a)	1 (a)	-
Surface Cu	2	-	-	-
Underground Cu	1	-	1 (b)	-
Underground Ur	1	-	-	-
Au/Ag**	-	1	1 (c)	1 (d)
Taconite	5	-	1 (e)	-
Quarries	4	2	-	-

* Magazines not examined at one coal mine because not permitted by management

** Two underground and one surface

(a) Two had many weeds and shrubs near magazines. One had 7.5 KV powerline overhead.

(b) People permanently working in detonator magazine.

(c) Cap magazine at an angle, almost teetering, and right under a large tree.

(d) Condensor blasting machines and det. cord stored in detonator magazine. Also overloaded HE magazine.

(e) Boxes of cast boosters stored at an angle and some on top of slurry boosters in plastic bags; "pig-tails" of some cast boosters stuck out and were stepped on by blasting foreman.

From time to time, the question arises as to where to store fuse lighters (ignitacord, pull-wire lighters, etc.). Ideally, such devices should be stored separately, but if this is impractical then they should be stored with detonators. The rationale for this is as follows: fuse lighters do not explode but their very nature can make them liable to inadvertent ignition. Thus, at worst, separate storage of fuse lighters can result in a fire but no explosion. Inadvertent ignition of fuse lighters in a detonator magazine can create an explosion but because of the relatively small amounts of explosives in detonator magazines such an explosion should be less disastrous than a fire and explosion in an HE magazine.

As shown in Table 9, 6 of 24 mines visited stored fuse lighters. One of these stored them separately, four of these stored them with detonators and one operation stored them with HE.

Magazine siting appeared adequate at most of the operations visited (Table 10). However, at 5 of 34 mines magazines appeared to be in violation of the American Table of Distances. We use the word "appeared" advisedly because many of the distances in Table 10 were "eye-balled" and could be enough in error for the magazine sitings to be in compliance with the Table of Distances. There were no MSHA citations of the magazines that we believe to be in violation. In part, this may be due to MSHA inspectors interpretation of what constitutes a barricade around a magazine.

Photos of different types of magazines are shown in Figure 1. Figure 1a shows a metal magazine. An earth-covered igloo-type magazine is presented in Figure 1b and a masonry magazine in Figure 1c. Figure 1d shows a drop trailer for storage of blasting agents.

Table 11 presents data on the proportion of non-metal magazines in current use. These data are important (as will be shown later) in estimating lightning hazards to explosive storage. That approximately one-quarter of all magazines are non-metal appears to be conservative. Estimates by knowledgeable people (IME) have placed this figure as high as one-half.

There is an MSHA regulation that requires all metal magazines to be grounded. The pros and cons of this requirement will be discussed later, what we present below are our observations of grounding practices. Visual observations (we made no measurements; indeed MSHA does not specify how "good" a ground is required) indicate that, with a few exceptions, the 22 mines that we visited and which had metal magazines were "properly"

TABLE 9.-OBSERVED STORAGE OF FUSE LIGHTERS

Mine	Material Mined	Fuse Lighters Storage
N	Cu	In separate magazine
P	Cu	In detonator magazine
O	Cu	In detonator magazine
T	Ag/Au	In detonator magazine
S	Ag/Au	In detonator magazine
R	Ur	In HE magazine*

* They claim that they were told to do so by MSHA (?)

Table 10. - Approximate Distance of Magazines from Various Installations

Distance / Operation	Non-Mine Housing† (Kft)	Mine Installations (Kft)	Highways (Kft)	Mine Haulage Roads (ft)	Barricades Around Magazine
Quarry AB	10	2	7.5	2700	Yes (c)
" AC	0.8	0.2 (a)	0.2 (a)	200	None
" AD	5	1.6	3.5	200	Partial
" AE	2.5	1.2	2.5	200	Partial
" AF	2.5	0.2 (a)	2.6	15	Partial
" AG	1.2	0.4 (a)	1.6	400	None
" AH	≈1	1.5	≈0.5	-	None
Surface Coal A	5	2	5	150	None
B	1.8	1	1	50	Partial
C	5	2.8	2.6	2800	None
D	2.3	8	2.6	100	None
E	3.5	0.2 (a)	3.5	150	None
F	2.0	1.9	1.3	100	Yes
G	5	8	5	100	Partial
H	4	8.5	5	500	None
I	11	0.5 (a)	20	300	None
Underground Coal J	15	2	20	1000	Fartial
K	3.5	0.9	6	1000	Partial
L	1.2	0.5 (a)	1.8	-	Partial
M	5	2	5	500	Partial
Taconite V	3.4	4.5	5	800	Partial
W	11	5.6	15	2800	None
X	25	18	18	11000	None**
Y	7.8	2.8	15	2000	None
Z	3	4	2	900	None
AA	5	1.5	6	500	None
Surface Cu N	11	5	1.2	7000	Partial
O	11	5	11	3000	Yes (c)
Underground Cu P	5	3	5	5000	Partial
Q	15	1	15	500	Partial
Ag/Au S	11	0.1 (b)	11	100	Partial
T	2.6	(d)	2.6	-	(e)
U	3.5	-	2.6	-	None
Ur	2.5	1	26	1000	Partial

* Mills, crushers, offices, repair shops, etc.
** Magazines grouped together in a fenced area

(a) Violates American Table of Distances
(b) Borderline according to American Table of Distances
(c) Berm around magazine area
(d) Fuse cap storage right against office
(e) Underground dugout for HE & BA

† Kft = 1000 ft.

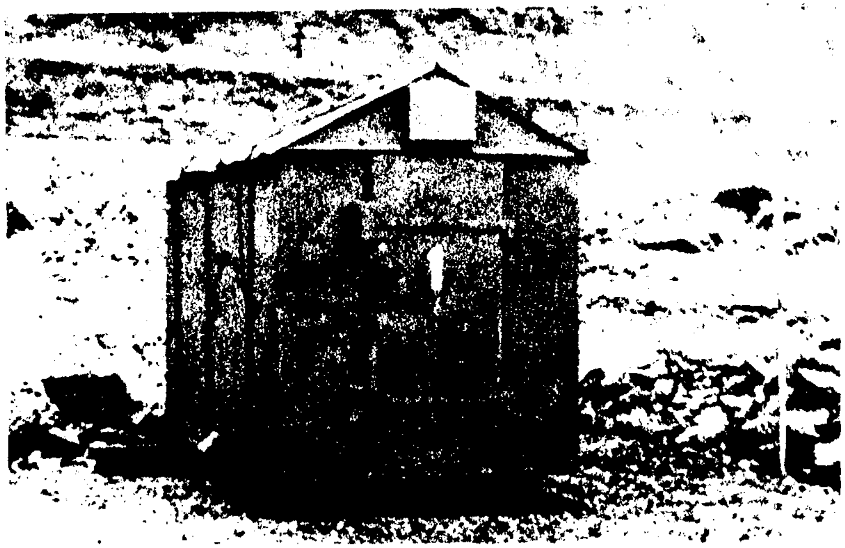

Fig. 1a. Metal Magazine on Wooden Blocks

Fig. 1c. Masonry Magazine with Metal Door

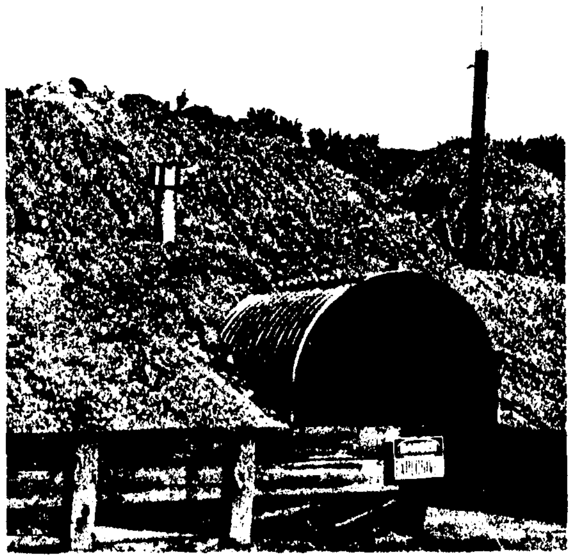

Fig. 1b. Metal-Covered "Igloo"

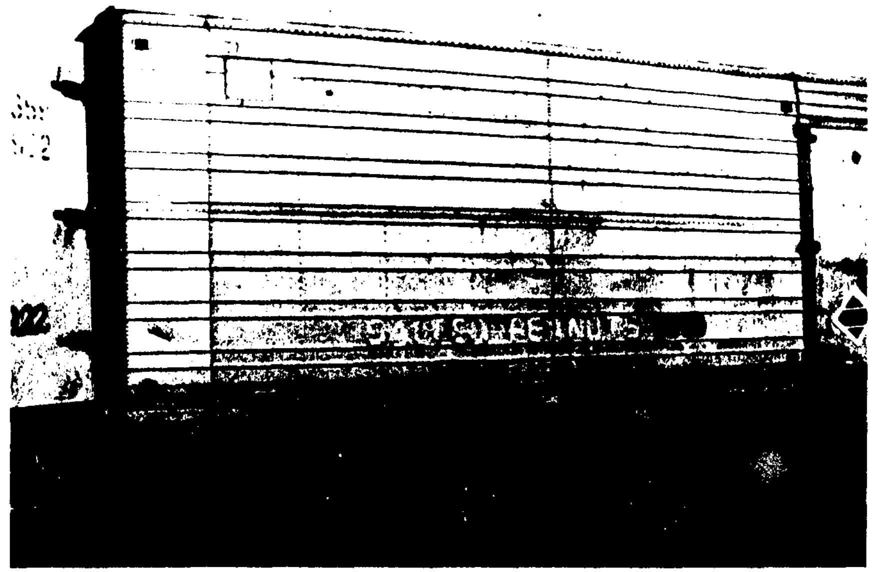

Fig. 1d. Drop Trailer Magazine for Blasting Agents

Fig. 1. EXAMPLES OF MAGAZINES FOR EXPLOSIVE STORAGE

TABLE 11.-NUMBER OF MINES VISITED THAT HAVE NON-METAL MAGAZINES

Mine	No. of Non-Metal Magazine	Comments
Surface Coal	2 out of a total of 9	Non-conductive roofs; steel doors close to ground.
Underground Coal	3 out of a total of 4	None had conductive roofs; steel doors 1/2 to 1 foot above ground.
Surface Cu	1 out of a total of 2	Conductive roof; steel door close to ground.
Underground Cu	1 out of a total of 2	Non-conductive roof, steel door about 3 feet above ground.
Underground Cu	1 out of a total of 1	All concrete with steel door close to ground.
Au/Ag	1[a] out of a total of 3	—
Taconite	0 out of a total of 6	—
Quarries	1 out of a total of 7	Metal roof; steel door.
Totals	10[b] out of a total of 34	—

[a] Dug out of solid rock underground.

[b] Really 9 of 34 since one Au/Ag mine had underground storage.

grounded; i.e., they had a substantial wire running from the magazine to a metal stake driven into the ground, with what appeared to be adequate bonding of the wire to the magazine and to the stake.

Furthermore, at least 16 of these magazines were on metal skids which sat directly on the ground (e.g., as shown in Figure 2a). These skids should provide as good or even better electrical ground than the wire-and-stake combinations. Three and probably six of these 22 magazines (all in Minnesota) were raised above ground on wooden blocks.

There is disagreement among the explosive suppliers as well as some MSHA personnel as to the actual function performed by the ventilation of explosive magazines. One school of thought maintains that the main or even sole function of ventilation is to keep down harmful fumes (e.g., nitroglycerin or fuel oil). Others believe that ventilation maintains humidity and temperature control within the magazine. We tend to favor the fume control school since it is hard to imagine how one can maintain consistent humidity and temperature control by a modest flow-through of ambient moist and hot air such as is commmon during the summer months in much of the country. At any rate, whatever its main function, it appears desirable to ventilate explosive magazines.

Different modes of ventilation are shown in Figures 1a, 1c, 1d, 2a, 2b and 2c. Note the difference in the ventilation systems of Figures 2a, 1c and 2b. All of the permanent magazines viewed had what appeared to be "adequate" ventilation systems.

Ventilation systems in the drop trailers that we saw were rather rudimentary (Figures 1d and 2c). Ten of the 34 mines and quarries visited had drop trailers in use. Six of these were at surface coal mines, three at quarries, and one at a taconite mine (another taconite mine had an empty trailer). Of the coal mine drop trailers, two had some form of ventilation, two had no ventilation, and no information was obtained for the remaining two. At the quarries, two drop trailers were ventilated and one was not. The empty trailer at one taconite mine was not ventilated and no information was obtained about the trailer at the other taconite mine.

Figure 2d shows the inside of a magazine, and in particular, the spacers at the wall that ensure that explosives cannot be stacked right against the walls to prevent air flow. Note the good practice, as required by regulations, of separating high explosives (foreground) and blasting agents (background).

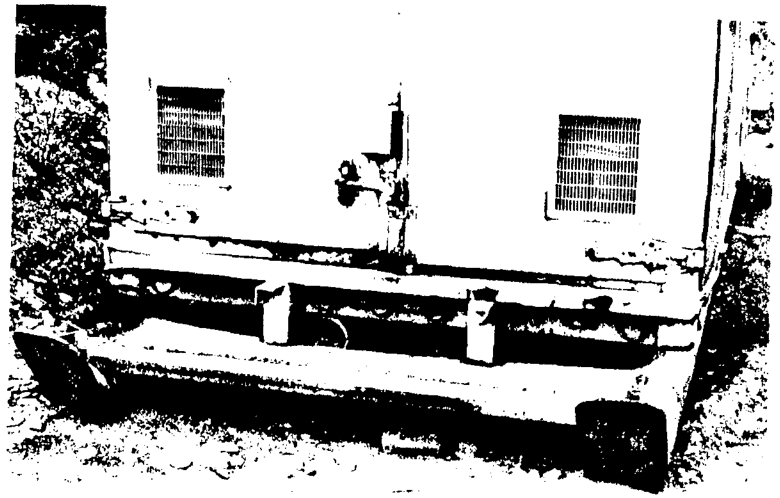

Fig. 2a. Metal Magazine With "Passive" Ventilation

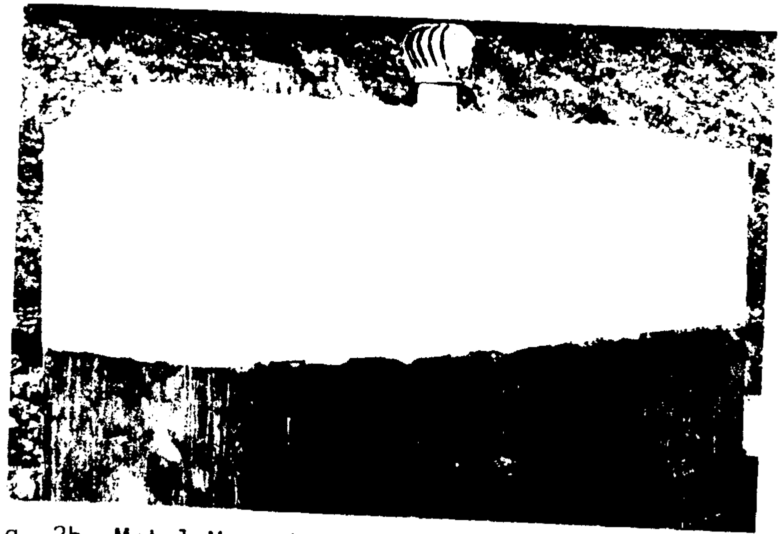

Fig. 2b. Metal Magazine with "Forced" Ventilation

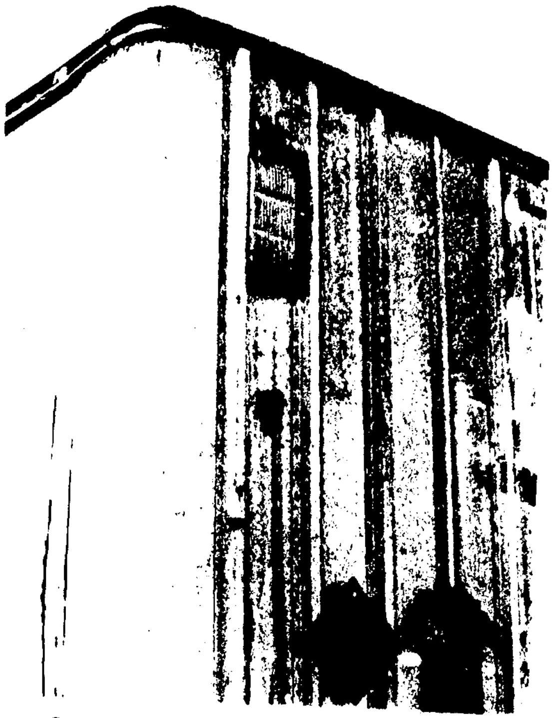

Fig. 2c. DROP TRAILER WITH "PASSIVE" VENTILATION

Fig. 2d. Inside of a Magazine with Wooden Stand-off at Walls

Fig. 2. EXAMPLES OF MAGAZINE VENTILATION

3.4 Comments from the Mining Community

At each mine visited we solicited comments from the person or persons interviewed about any possible improvements in the storage of explosives. These comments are summarized in Appendix B. Although all aspects of explosive storage were open to comment these discussions almost invariably turned to storage regulations and their enforcement. Most of these comments can be paraphrased as: "Existing regulations are good but...". Most frequently, the "but" was followed by complaints about the inconsistency of inspections; i.e., one inspector's demands for compliance with regulations may be just the opposite of those of the subsequent inspector. This problem is created by a lack of specificity of some of the regulations which permit "judgement calls" on the part of the inspectors.

A thoughtful comment (from Mine P in Appendix B) points out the necessity to consider the cost of protective measures in terms of the cost of the accident, provided that steps are taken to minimize exposure of personnel to the accident.

A requirement that was questioned several times was that of locking of AN-FO storage bins. Apparently some of the mine personnel felt that this was "guilding the lily", and a "regular pain" since locks on the bins corrode rapidly.

A quarry superintendent claimed that he had no control over storage conditions and practices of magazines used by a contractor. This is in accord with our observation at a Ag/Au mine (see Table 8).

The desirability of combining all Federal regulations on explosive storage into a single booklet of a few pages was specifically mentioned by one quarry superintendent and implied by several other people who were interviewed.

Also, there were some comments and complaints about the requirement of covering all potential spark-generating items (e.g., nails) with mastic or some other non-sparking material. The consensus was that this requirement is a carry-over from the past when black powder was used extensively in mining.

4.0 MAGAZINE EXPLOSIONS

Much can be learned from the examination of records of past explosions. Careful evaluation of the circumstances surrounding each accidental or deliberate explosion may provide enough information for effective countermeasures to prevent the recurrence of these hazardous situations. Thus, each such explosion should be viewed as a more-or-less controlled experiment (obviously a terribly wasteful one) and as such the utmost care should be exercised to record all details of the accident. Unfortunately, this is rarely done. In many records of past explosions even the most fundamental details are lacking; e.g., the explosives involved.

Explosions during explosive storage are rare, and records of such explosions are hard to find. For magazine explosions during the last decade we searched MSHA reports, questioned MSHA personnel and technical staffs of IME and explosive manufacturers, as well as the people interviewed during our mine visits. We also searched the HSAC files that we obtained during our study of blasting practices in surface mines (Bureau of Mines Contract J0366017) and obtained the helpful cooperation of HSAC in searching their current files. These searches drew a complete blank since there is no such category as explosive magazines or explosive storage within the HSAC files. Interviews with mining personnel also failed to uncover any explosions that were not previously known to us. Thus, our data base was provided entirely from examination of MSHA accident reports and contacts with MSHA and IME.

The other set of accident data that was acquired was abstracted from a 1930 IME publication by R.A. Assheton entitled "History of Explosions". This has accident data going back to the Civil War and even beyond and includes accidents up to 1927. Since explosive storage conditions during that period were quite different from modern-day storage, in what follows, past-decade and "ancient" times accident histories will be first examined separately and the conclusions of the examination will then be combined whenever warranted. Because data are scarce it was decided to consider all magazine explosions for which we had some information and not only magazine explosions on mine property.

4.1 Past-Decade Magazine Explosions

Data on ten magazine explosions that occurred between 1970 and 1977 (we could find no reference to any magazine explosions since 1977) are presented in Table 12. Listed are location of explosion, its date, its probable cause and the explosive

TABLE 12.-SUMMARY OF MAGAZINE EXPLOSIONS DURING THE LAST DECADE*

Location	Approximate Date	Source of Information	Explosive	Probable Cause
AL	Early 70's	IME	Dynamite	Deliberately initiated by EB's (a)
FL	1972	**	Dynamite	Not established; probably bullet impact
AK	Mid 1970's	IME	Dynamite	Deliberately initiated by fuse caps (b)
MO[c]	1973	MSHA report	Dynamite	Not established; probably bullet impact
AZ	1975	MSHA Explosives Manufacturer	Bagged AN-FO[d]	Armor-piercing bullet impact.
VT	1975	MSHA report	Black powder, Dynamite & detonators in a wooden "day box"	Fire apparently caused by lightning strike nearby
KY	1975	MSHA report	Detonating cord & fuse caps	Cutting lock with an acetylene torch
PA	1975	IME	Dynamite	Fire possibly as a result of a lightning strike on an adjacent wooden dock
NY	1976	MSHA report	Slurry blasting agent premix	Fire of unknown origin
OH	1977	BATF	Dynamite	Sabotage

* Only 3 of the 10 explosions listed above occured on mine property.

** Writer was involved in the litigation following this explosion.

[a] Two drunks broke into the magazine and set off the explosion with an EB.

[b] Two boys broke into the magazine and set off the explosion with a fuse cap.

[c] Two magazines (about 200 feet apart) exploded.

[d] A small amount of dynamite stored with the AN-FO was presumably hit by an armor-piercing bullet. Several shots were fired before the explosion occured.

involved. It is noteworthy and very disturbing that six of these ten explosions were deliberate! Two of the ten may be attributed to fires started by lightning. Of the remaining explosions, one was due to a fire of unknown origin and the other due to heat, sparks or flame generated during an attempt to remove a magazine lock cover by cutting it with a welding torch!

Overall, there were ten magazine explosions per decade. This is the figure that we want to compare with the earlier ("ancient" time) data. It should also be emphasized that seven of the ten explosions involved explosives supplier or distributor magazines. The only magazine explosions on mine property were the ones in Vermont, Kentucky and Ohio. (See Table 12).

The sequence of events of the 1973 explosion in Missouri is of considerable interest, even though the cause of the accident is still conjectural. Two magazines that contained 60K lbs. and 40K lbs. of dynamite and were about 200 feet apart exploded. The unbarricaded inter-magazine separation given in the American Table of Distances is 300 feet for 60K lbs. and 250 feet for 40K lbs. Thus, taking these distances as gospel, explosions of either magazine should have shot the other magazine and indeed it did. Even more fascinating is the extensive damage, but no direct explosion of contents, of two other magazines about 400 feet from the explosion site. According to the American Table of Distances, no explosion was to be expected and none occurred.*

4.2 Magazine Explosions During the Period 1884-1926.

Data for magazine explosions over about four decades of "ancient" time are shown in Table 13. In addition to the same sort of information as listed in Table 12, this table also contains a general description of the materials of construction of the magazines. Of the 27 explosions in Table 13, seven were attributed to practices now forbidden such as smoking, improper use of steel tools and live steam and wood stoves inside magazines. An additional four explosions were attributed to fires of unknown origin and one explosion was the result of a forest fire. Three explosions may have been deliberate - two arson and one bullet impact. Six explosions were directly attributed to lightning strikes. All of the six involved magazines constructed of non-conductive materials. No cause could be established for the six remaining explosions.

* It should be noted that one of the two damaged magazines contained electric blasting caps. Some of these did explode as a result of fires created during the destruction of this magazine.

TABLE 13.-MAGAZINE EXPLOSIONS PRIOR TO 1927*

Date	Location	Structure	Contents**	Cause
1884	Kimberley, S. Africa	Wood; iron roof[a]	BP; Dyn; Det	Fire, possibly due to Smoking
1886	Chicago, IL	Brick; slate roof	BP; Dyn	Lightning
1891	Rome, Italy	Massive limestone	BP; Det; Fuses	Unknown
1903	Lowell, Mass.	Brick	BP; Dyn	Fire during clean-up
1903	Chattanooga, TN	Brick	Dyn	Lightning
1905	Hazleton, PA	Stone: wood doors	Dyn; Det	Stove-generated fire
1906	Cobalt, Canada	Wood	Dyn	Forest fire
1906	Yreka, CA	Stone	Dyn	Rifle bullets
1906	Bridgeport, Conn	?	BP; SP	Unknown
1907	Mt. Carmel, PA	Wood, iron roof	BP; Dyn; Det	Unknown; possibly live steam
1908	Beaver Meadow, PA	Wood	BP; Dyn; Det;	Lightning
1908	Cle Elum, WA	Stone, Brick	BP; Dyn	Possibly smoking or rough handling of BP
1908	McAlester, OK	Limestone walls	BP; Dyn	Lightning
1908	Batuco, Chile	Wood; iron roof	BP; SP	Unknown
1909	Plymouth Mtg. house, PA	? (b)	Dyn	possibly live steam
1910	Jeanette, PA	Wood; iron roof	BP; Dyn; Det	Fire; possible arson
1910	Cabot, PA	Wood & tar paper	BP; Dyn; Det	Unknown; poss. smoking
1911	San Jose, Costa Rica	Brick	BP; Dyn; SP	Fire of unknown origin
1912	Oakdale, CA	Wood; iron roof	BP; Dyn	Fire, possibly arson
1912	Cleveland, OH	Brick	BP; Dyn	Unknown
1913	Martin, PA	Steel[c]	Dyn; Det	Unknown
1913	San Antonio, Spain	Plastered cave	Dyn	Lightning
1914	Canal Zone	Concrete	Dyn	Fire of unknown origin
1914	Panama, Canal Zone	Stone	BP; Dyn; Det	Fire of unknown origin
1922	N. Charleston, SC	San-filled wood boxes	BP	Improper use of Steel tools
1924	Manila, Phillipines	Concrete; Iron roof	BP; Dyn; Det; TNT	Unknown
1926	Lake Denmark[a], NJ	Brick and Tile	TNT	Lightning[c]

* Abstracted from R.A. Assheton "History of Explosions" (1930)
** BP = Black powder; Dyn. = Dynamite; Det = detonators

(a) Multiple explosions
(b) Magazine and "thawing house"

(c) Brief fire as a result of a strike preceded explosion. Magazine in which the initial explosion took place was equipped with a lightning conductor of the "ordinary type".

Overall, there were about seven magazine explosions per decade.

4.3 Examination of "Past" and "Present" Magazine Explosion Data

The main purpose for the study of magazine explosions histories is to establish explosion causes and trends so as to prevent the recurrence of such disasters in the future. One obvious correlation to be sought is that of explosion frequency and nature of explosive contents. This is done in Table 14 for "past" and "present" data. The results are slightly surprising. Of the 37 combined explosions, only ten may possibly have involved detonators - the most sensitive type of mining explosives. The reason for the uncertainty is that in nine of ten such explosions, other explosives (black powder and/or dynamite) were stored with the detonators. Seven explosions involved high explosives - dynamite or TNT. An additional seven explosions involved combined dynamite and black powder storage. Four explosions involved only black powder, and two explosions primarily blasting agents, although one of these two magazines also contained a small amount of dynamite.

That only slightly more than one-quarter of the explosions examined involved detonators is surprising at first glance. However, when one considers that most facilities have only one detonator magazine, and many facilities may have more than one explosive magazine (see Table 5), this result becomes less unexpected. Also, the total poundage of explosive contents is vastly less in detonator magazines than in explosive magazines. It may be that more detonator magazine explosions remain unreported and unrecorded than explosives magazine explosions which produce the much greater "bang".

Again, on the basis of sensitivity, one might expect more trouble with black powder storage than with dynamite storage. Because of mixed storage and because black powder use is almost negligible in recent years, no such conclusion can be drawn from the data in Table 14. Indeed, at face value, one might erroneously conclude that black powder is safer to store than dynamite, since, in the period when black powder was still used extensively, there are six explosions of dynamite magazines and only four of black powder magazines, What makes such a conclusion invalid are the seven magazine explosions that contained both dynamite and black powder for which it is impossible to determine which material triggered the explosion. Noteworthy is the fact that two recent explosions involved primarily blasting agents. Thus, blasting agents are not quite as safe as some suppliers want us to believe.

TABLE 14.-NUMBER OF MAGAZINE EXPLOSIONS AS FUNCTION OF MAGAZINE CONTENTS

	Time Period	
	1884-1926	1970-1982
Black Powder	4[(a)]	0
Black Powder & Dynamite	7	1
Black Powder, Dynamite and detonators	7	0
Dynamite	6	6
Dynamite and Detonators	2	0
TNT	1	0
Detonating Cord and Fuse Caps		1
Blasting Agents	0	2[(b)]
Totals	27*	10**

(a) One of these also had detonators stored with the black powder.

(b) One of these had a small amount of dynamite stored with the blasting agent.

* Possibly 3 of these were deliberately set; 13 caused by fire or heat; 6 caused by lightning; 6 unknown causes; 1 improper use of tools.

** 6 of these were deliberately set; 4 of these caused by fire; see Tables 12 & 13.

Magazine explosions as a function of cause and contents are examined in the footnotes to Table 14 and more particularly in Table 15. Combining all fire and flame-produced explosions (other than those attributed to arson) into a single "fire" category one finds that there are 13 such explosions listed in Table 15. Break-down of this category into the explosives involved shows: three explosions of dynamite only, one of blasting agents, one of detonators only, two of high explosives stored with detonators, three of dynamite stored with black powder, and three of magazines that contained dynamite, black powder and detonators.

If one combines bullet impact, arson, etc. under the heading of "deliberate" explosions, there are nine such explosions in our data base and they constitute the second largest explosion category. Seven of these nine involved only dynamite. As already mentioned, six of these explosions occurred during the past decade.

The next most frequent category is "lightning", but six of these occurred long ago and the two recent ones are the results of lightning-generated fires (which are counted in the "fire" category) rather than explosions that occurred almost immediately after the lightning hit on a magazine. Among this category are three explosions involving high explosives (dynamite or TNT), two explosions of magazines that contained both dynamite and black powder, and one explosion of a magazine that contained a mixture of dynamite, black powder and detonators!

Now let us consider the significance of ten magazine explosions during the 1970-1980 decade as compared to 27 explosions in the roughly four decade period of 1884-1926. On a <u>per decade basis</u>, there were ten explosions during 1970-1980 period and slightly less than seven explosions during the 1884-1926 period. This is quite disturbing since many of the poor practices such as stoves in magazines, storage of detonators in the same magazine as high explosives, etc. no longer exist, and one would expect a decrease rather than increase in explosion frequency. Of course, there are many more magazines now than there were in the past, but this appears to be counteracted by the realization that annual consumption of "sensitive" explosives (expected to be related to annual storage) for the years 1970-1980 is not very different from that for the early years of this century. According to Table 12 of the 175th Anniversary Edition of DuPont's "Blasters Handbook", the average combined consumption of permissibles, "other high explosives", and black powder was about 500K lbs./year over the period 1912-1927. According to the same source, and additional data taken from Bureau of Mines Mineral Industry Surveys, for the period 1970-1980, the combined

TABLE 15.-MAGAZINE EXPLOSIONS AS A FUNCTION OF CAUSE AND CONTENTS
(Combined 1884-1926 and 1970-1980 data)

Accident Cause	No. Of Accidents	Materials that Exploded
Bullet impact	4	Dynamite [a]
Deliberate (Sabotage, "pranks" arson, but not bullet impact)	5	3 dynamite[b], 1 B.P. and dynamite; 1 B.P., 1 Dyn. & Detonators.
Lightning	8	3 dynamite[c]; 3 B.P. and Dyn.[c] 1 TNT; 1 B.P., Dyn. & Detonators
Smoking[c]	3	2 B.P. Dyn. & Detonators: 1 B.P. and Dynamite
Fire (other than deliberate or lightning-caused)	7	2 Dynamite; 2 B.P. and dynamite 1 dyn. & Deton.; 1 B.P. Dyn., and Deton.; 1 blasting Agent premix [d]
Possible contact with live steam	2	1 Dynamite, 1 B.P. Dyn & Deton.
Welding with Acetylene torch	1	Deton. cord & fuse caps
Improper use of tools	1	B.P.
Unknown	6	2 B.P.: 1 B.P. & dynamite; 1 B.P. and deton.: 1 Dyn. & Deton.; 1 B.P., dyn., deton., and 1 TNT.

[a] One of these in 1884-1926 time period; another of these primarily AN-FO but contained several boxes of dynamite.

[b] 3 of these occurred in the last decade.

[c] One of these preceeded by a fire of nearby combustible material.

[d] This is the only "fire" accident in the 1970-1980 decade.

average consumption of permissibles, other high explosives and water gels and slurries is about 600K to 700K lbs/year. Although it is not clearly stated, the "water gel and slurry" category of recent years probably includes gels that are blasting agents rather than high explosives. Thus, the annual consumptions of "sensitive" explosives during 1970-1980 and during the early 1900's are quite comparable, and it appears that the main reason for the recent increase in magazine explosions is not due to an increase in the storage of "sensitive" explosives.

The real cause behind the increased frequency of magazine explosions is the large increase in deliberate explosions! In the period 1970-1980, six of ten magazine explosions were deliberate (see Table 12) while during 1884-1926 only three of 27 magazine explosions may have been deliberate (see Table 13). This suggests that future protective measures should emphasize the elimination of "human hazards" rather than of natural hazards since the latter, but not the former, now appear to be under reasonable control.

5.0 ESTABLISHED AND POTENTIAL HAZARDS IN THE STORAGE OF EXPLOSIVES

5.1 Deliberate Explosions

In recent years, as discussed in Section 4.0, six of ten magazine explosions were deliberately set. Most likely, three and possibly four of these six involved break-in and entry into the magazines before the explosions were initiated. Thus, unauthorized entry into magazines is an established hazard that must be faced. Means of preventing unauthorized entry will be suggested in Section 8.0. However, it appears that none of the viable preventive measures are fool-proof.

Another hazard that is just as difficult to control as unauthorized entry is the shooting at magazines with armor-piercing ammunition. It is conceivable that, at great expense and even greater reluctance on the part of magazine owners, magazines can be modified to be resistant to penetration by armor-piercing bullets, but what happens if such magazines are shot at with bazookas?

It is clear from recent magazine explosions that the major present-day hazard in explosive storage is due to criminal activity or sheer idiocy masquerading as malicious pranks.

5.2 Fires

It is well known that fire (or excessive heat), no matter how generated, is a great hazard to all explosives - even those of the most insensitive variety. This has been realized for a long time and magazines are required to be built primarily (at least on the outside) of incombustible materials and their immediate surrounding areas must be kept clear of brush, dry grass, etc. Nevertheless, in the last decade there were four magazine explosions as a result of fire or heat. Two of these fires may have been started by lightning. One explosion was the direct result of excessive heat, flame or sparks generated during an attempt to remove a magazine lock by cutting with an acetylene torch. The origin of the fire preceeding the one remaining explosion remains undetermined. Clearly, fires are still, and will always remain, a hazard in explosive storage, or for that matter, in any situation that involves explosives.

5.3 Electrical Hazards

Since explosive magazines are very rarely provided with electrical power, any electrical hazards are of external origin. Amongst such potential hazards are: lightning, power lines and static electricity. These will now be examined in reverse order.

5.3.1 Static Electricity

Probably this is the least likely electrical hazard to stored explosives. This hazard applies almost exclusively to detonator magazines storing electric detonators, all of which are now provided with anti-static shunts, and are stored (or should be stored) in closed, non-conductive containers. Furthermore, for metal magazines, even with ground connections in the megohm range, any static charges will be bled-off in a fraction of a second. Perfectly insulated metal magazines, conceivably, can have their metal shells acquire electrical charges but these charges will not penetrate to the interior of the magazine (Faraday cage effect). Such a charged magazine can give a nasty shock to a person touching the magazine and in a combination of most unlikely events, it can be a hazard to electric detonators (with dangling leg-wires) that are being returned or taken out of the magazine. A metal magazine has the further advantage that it will remove most of a static charge built up on a person (by whatever means) who contacts the magazine; e.g., when he is unlocking the magazine. If the metal magazine is grounded (even very poorly) all the charge on the person will be dissipated. Upon contact with a perfectly insultated metal magazine, substantially all the electrostatic energy on the person will be dissipated if the capacitance of the magazine is, as expected, much larger than that of a person.* Accordingly, from the point of view of eliminating electrostatic hazards, it may be desirable, to have metal magazines electrically grounded. Indeed, this appears to be the major justification for the grounding requirement in current MSHA regulations. However, when one considers the minute probability of electrostatic charging resulting in an explosion of stored explosives, and recalls that most metal magazines are inherently "grounded" through their metal skids (see Figure 2a), the MSHA requirement may be more of a nuisance than an effective protective measure.

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* The energy of a charged person is $\frac{Q_1^2}{2C}$ where Q_1 is his charge and C_1 is his capacitance. The energy of an uncharged magazine is, of course zero. Upon contact, the energy dissipated is: $\frac{Q_1^2}{2C_1}\left(\frac{1}{1+C_1/C_2}\right) \simeq \frac{Q_1^2}{2C_1}$ if $C_2 >> C_1$ where C_2 is the capacitance of the magazine. If $C_2 >> C_1$, upon contact $V_2/V_1 = (C_1/C_2) << 1$. Thus, potentially dangerous voltages are minimized (V_2 is the voltage on C_1 and C_2 when connected in parallel).

For non-conductive magazines the effects of electrostatic charging are more difficult to evaluate. Very severe external charging conditions can conceivably induce electrostatic charges on electric detonators inside a magazine. In order to produce an explosion, these unlikely situations must then be followed by a discharge through a sensitive portion of one or more detonators. The sequential occurrence of two or more highly improbable events makes the probability of a static-generated explosion extremely small. Indeed, there is no record of such an explosion during explosive storage. It may be prudent, however, not to enter a non-conductive magazine shortly after the passage of a severe sandstorm or snowstorm or the passage of low-lying thunder clouds. This will permit natural dissipation or reduction of electrostatic charges before any movement of charged detonators can conceivably result in a discharge that can initiate the detonator.

5.3.2 Proximity of Power Lines

Proximity of high-power electrical distribution lines can conceivably induce electrical currents on wires of electric detonators stored within a non-conductive magazine. For shunted and folded detonator legwires this should not create a hazard because any induced voltages will be of equal magnitude and polarity on both legwires and consequently there can be no current flow through the bridge wire. Indeed this will be the case even for unshunted legwires. A broken power line that contacts a non-conductive magazine also presents no hazard unless arcing to ground creates a strong brush or grass fire that engulfs the magazine.

Because of the Faraday cage effect, induction is no hazard whatsoever to metal magazines. Arcing of a broken power line to a metal magazine can conceivably burn through a thin metal sheathing on the outside of a magazine and ignite any flammable material on the inside of the magazine. To avoid such a situation (unlikely though it is) it is best to locate magazines away from power lines at least as far as the distance between supports of the power line to eliminate the possibility of contact between a broken power line and a magazine. This separation will also greatly reduce the chance of a grass or brush fire propagating to the magazine if such a fire is generated by the arcing of a broken power line at some distance from the magazine.

In summary, it appears that as far as danger from nearby power lines is concerned, metal magazines present a higher (though still very low) risk than masonry magazines. This difference in risk primarily reflects the differences in heat conductivity of these different structures. Heat from a relatively short-lived grass or brush fire may possibly generate dangerous temperatures inside a metal magazine but not in poorly conducting masonry or brick magazines. Furthermore, there is the possibility (again remote) of a burn-through of the skin of a metal magazine and no such possibility in a non-metallic magazine.

5.3.3 Lightning

The indirect effects of lightning; i.e., the generation of nearby fires, in causing magazine explosions have already been mentioned. What we now want to consider are direct effects which are distinctly possible because of the tremendous energy contained in a lightning stroke. What complicates such considerations is the necessity of establishing the conditions not only for the interaction of a powerful external stimulus with explosives protected by various external structures, but also by the realization such interactions are at best rather infrequent. There is also the distinct possibility that even if the hazard conditions are completely defined, adequate protective measures may be so expensive as to preclude their implementation for what appears to be a most infrequent hazard.

First, let us examine past history. In the past decade, there were no recorded magazine explosions caused directly by lightning (see Table 12). During the period 1884-1926, there were six magazine explosions that were attributed to lightning strikes. All these magazines were constructed of non-conductive materials. Complicating the picture is the fact that only three of these magazines contained only high explosives (dynamite or TNT). The remaining magazines contained various types of explosives. Two of the other magazines were loaded with dynamite and black powder, while in one magazine there was dynamite, black powder and blasting caps! Thus, in three of the six magazines it is impossible to tell which material initiated the explosion. In all six instances, there was complete explosion of all contents. The above provides direct evidence that stored high-explosives can be initiated by lightning, and circumstantial evidence that black powder and blasting caps, both of which are more sensitive to flame and heat than high explosives, can also be initiated. Then, the question arises what is the risk of lightning-generated explosion of modern explosive magazines? The majority of these are now metal,* they no longer contain detonators and explosives

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* See Appendix C

in the same magazine, and essentially no black powder is stored since its use in mining is currently negligibly small. To answer the question we need to:

1. estimate the frequency of lightning strikes on explosive magazines, and

2. define conditions under which such strikes can initiate explosion of the contents.

In item 2 metal and non-metal magazines must be considered separately.

Several simplifying assumptions have to be made before one can estimate the frequency of lightning strikes on permanent magazines (excluding drop-trailers). These are:

- Within a region of a given annual thunderstorm frequency lightning strikes occur randomly.

- The presented surface area of a building and its height control the number of strikes it receives, provided the building is "out in the open".

- Lightning strike frequency on such buildings follow a Poisson statistical distribution.

- There are at least 22,000 explosive magazines in the U.S. (see footnote (a) of Table 16).

Our analysis on the basis of these assumptions follows Golde "Lightning Protection" Chemical Publishing Co., New York (1975), Chapters 3 and 4. Details are given in Appendix C. Results are summarized in Table 16. It was assumed that each active mine had two magazines and all these magazines were parallelepipeds of $6x3x3m^3$. The important parameter in Table 16 is λ, the expected number of yearly lightning strikes on magazines in the U.S. For fixed magazine dimensions, λ is directly proportional to the total number of magazines and the number of thunderstorm days per year, or more precisely, to the number of strikes per km^2 per year. No attempt is made to distinguish between violent and weak thunderstorms, and at first it is assumed that all magazines are "out in the open"; i.e., there are no protective devices nor is the terrain or vegetation such as to make the magazine electrically "unobtrusive". For these conditions, as shown in the top grouping of Table 16, there is a high probability that between 40 and 60 magazines are struck yearly.

Table 16.- ESTIMATE OF THE NUMBER OF MAGAZINES YEARLY STRUCK BY LIGHTNING

Annual Thunderstorm Days	Number of Magazines	Annual Lightning Strikes/Km^2 *	Expected Number of Magazines Struck/Year**	Probability that λ is within the range of X_2 and X_1 ***		
	(N)	(n)	(λ)	(p)	(X_1)	(X_2)
60	22,000[a]	9	50	0.276	48	52
60	22,000	9	50	0.564	45	55
60	22,000	9	50	0.862	40	60
60	17,600[b]	9	40	0.616	35	45
60	17,600	9	40	0.903	30	50
40	17,600[b]	6	27	0.615	23	31
40	17,600	6	27	0.898	19	35
40	8,800[c]	6	13	0.510	12	15
40	8,800	6	13	0.872	8	18

* According to Golde, "Lightning Protection" (1975), pp. 20-22 and 40-41.

** Ibid, $\lambda \simeq Nn[LW+4H(L+W)+4\pi H^2]$ where the term in square brackets is the presented area of a typical magazine of length L≡6m, width W≡3m and height H≡3m, but expressed in km in the equation.

*** It was assumed that λ follows a Poisson distribution but the probability that it lies within the range X_1 to X_2 can be approximated accurately from a normal distribution of $t_1=(X_1-1/2-\lambda)/\lambda^{1/2}$ and $t_2=(X_2+1/2-\lambda)/\lambda^{1/2}$.

(a) Assumed two magazines at each of 11,000 active mines and all "out in the open".

(b) Assumed two magazines at each of 11,000 active mines but only 80% "out in the open" (see Appendix C).

(c) Arbitrarily chosen as 1/2 the magazines in (b) to get some indication of conditions around the turn of this century.

In Appendix C, it is shown that on the basis of our observations, coupled with statistical considerations, the fraction of magazines "out in the open" is about 0.8. When the number of magazines (in the top grouping) is corrected by this factor, the second grouping in Table 16 shows that there is a high probability that between 30 and 50 magazines will be struck by lightning every year.

If one considers that the average number of annual thunderstorm days in all mining areas is 40 rather than 60, the expected number of yearly strikes is 27 with a high probability that this number lies between 19 and 35 (see third grouping in Table 16).

Discussions with Professor E. P. Krider, a nationally recognized authority on lightning, indicated that a good average value for all mining regions in the U.S. is six strikes per km per year. This is the value that we used in conjunction with the 40 annual thunderstorm days.

The above analysis indicates that lightning hitting a magazine <u>is not expected to be a rare event</u>. Nevertheless there are <u>no</u> reported mishaps due to such strikes over the last 20 years.

In Table 13 it was shown that during the four decade period of 1884 to 1926 there were six magazine explosions attributed to lightning strikes. All these magazines were constructed of non-conductive materials. We have no reliable means of estimating the total number of magazines that were in use during those four decades. As discussed in Section 4.0, the number of magazines for storing high explosives or detonators was probably not very different during 1912-1926 that it is now. We have no data for the years prior to 1912. To get some idea of the fraction of magazines struck by lightning which then explode, we have <u>arbitrarily</u> assumed that the total number of magazines <u>"out in the open"</u> during 1884-1926 is one-half of the number that we estimate to be in the open currently. As shown in the bottom grouping of Table 16, this leads to an expected number of 13 annual strikes on magazines or 520 strikes in four decades. Since there were six explosions in that period the estimated fraction of explosions per strike is 6/520 or 0.0115.

Now, let us provisionally assume that metal magazines are <u>immune</u> to lightning strikes and only non-metal magazines can be exploded by lightning. As shown in Table 11, the expected fraction of non-metal magazines <u>now</u> in use is about one-quarter of the total. Applying this proportion to the data in the third grouping of Table 16, the expected number of yearly hits on non-metal magazines out in the open is about seven or 140 hits in 20 years. If we assume that proportion of explosions per strike was the same in the last two decades as it had been in the four decades of 1886-1926, the expected number of lightning-generated explosions for the past 20 years is $140 \times (6/520) \simeq 1.5$. Even though no explosions were recorded, this is not an unreasonable result, when one considers the uncertainties in the estimate and the usual statistical fluctuations.

To summarize, at the present level of explosive use, during a 15 year period one might expect one explosion of a high explosive or detonator magazine due to lightning.

Thus far, we have excluded drop-trailers from our discussion of lightning hazards. The possibility of lightning-generated fires or explosions in drop-trailers will be addressed in Section 5.3.5.

5.3.4 Lightning Hazards in Non-Metal Magazines

So far it has been tacitly assumed that metal magazines are immune to lightning-generated explosion of their contents but magazines made primarily of non-conductive materials are not immune. Justifications for the former are given in Appendix D and ways by which lightning can initiate explosion inside non-conductive magazines are summarized below.

The return stroke of a lightning flash through a non-conductive magazine encounters a path of non-uniform high resistance. This rapidly creates regions of very high temperature. Because the stroke is of high frequency and because the usual path will be along rain-wetted roofs and walls, these high temperature regions will be primarily on the outer surface of roof and walls (skin effect. Per se, this heating phenomenon is not expected to be dangerous. However, the rapid deposition of heat in relatively small regions (at any rate thin regions) can literally explode these regions. Projectiles thus created can be a hazard to explosives in the magazines. A variant of this scenario involves what in effect is a "steam boiler explosion" of rapidly heated moisture in the materials of construction of a magazine.

Since non-conductive magazines are not Faraday cages, lightning phenomena can induce electrical fields within such magazines. This can occur during the nearby passage of a charged cloud or a nearby lightning strike. Explosion hazard of the magazine contents for this scenario is confined to detonators and primarily to electric blasting caps. However, as already discussed, this hazard is minimal if all detonators (really we are referring mainly to EB's) are as received in their shipping containers. A much more risky situation develops if the magazine has some metal parts; e.g., a metal door and/or a metal roof. These can constitute moderately large condensors (of the order of several thousand picofarads) and store very large energies. They are certainly a danger to personnel and can be a danger to detonators.

Potentially even more hazardous is a "side-flash" within the magazine. A side-flash can occur if the return stroke on its passage through the structure to ground finds a lower resistance path close enough to break down the air between the original path and the preferred path. This side-flash, though of short duration, can be extremely hot - may be as hot as several thousand degrees Kelvin. Obviously, such a side-flash near any kind of explosive can be most dangerous. It is expected that side-flashes are more likely to occur when a "non-conductive" magazine has a metal roof and a metal door since these metal parts are certainly preferred paths.

Both the charged condensor and, to a much lesser degree, side-flash hazards can be reduced by a good (low resistance) bond between metal roof and metal door and a ground connection to one or the other (whichever is more convenient). An adequate ground connection can be of quite high resistance (kiloohms or even a megohm) and still dissipate most of the charge on the "condensor" in a matter of millisecs. Not all non-conductive magazines have metal roofs but all have metal doors. If both are present, an electrical bond between them can eliminate side-flashes from roof to door or vice-versa, but it will <u>not</u> eliminate side-flashes to either from some other portion of the structure. Grounding or not grounding of one or the other or both will have little effect as far as side-flashes are concerned. For these magazines, about the only viable safeguard is to store explosives as far as possible from metal doors and to keep stacks of explosive containers low and far-away from metal roofs.

5.3.5 <u>Lightning Protection</u>

Lightning protection systems are required for all magazines by the State of Arizona. Examples of such systems are shown in Figure 3. They consist of either a single wooden mast with an air terminal at its top connected to ground by a stake and located at some distance from the magazine (Figure 3a), or two masts with a wire strung between them and ground connections at either end (Figures 3b and 3c). Certainly, these systems offer some degree of protection but they <u>do not</u> eliminate the lightning

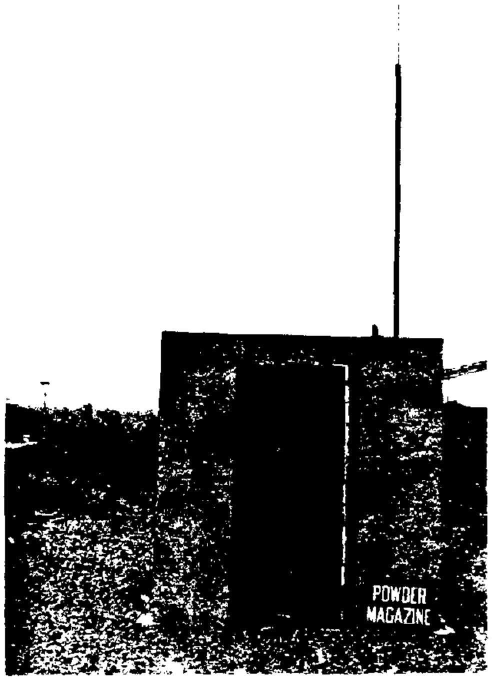

Fig. 3a. One-Mast System

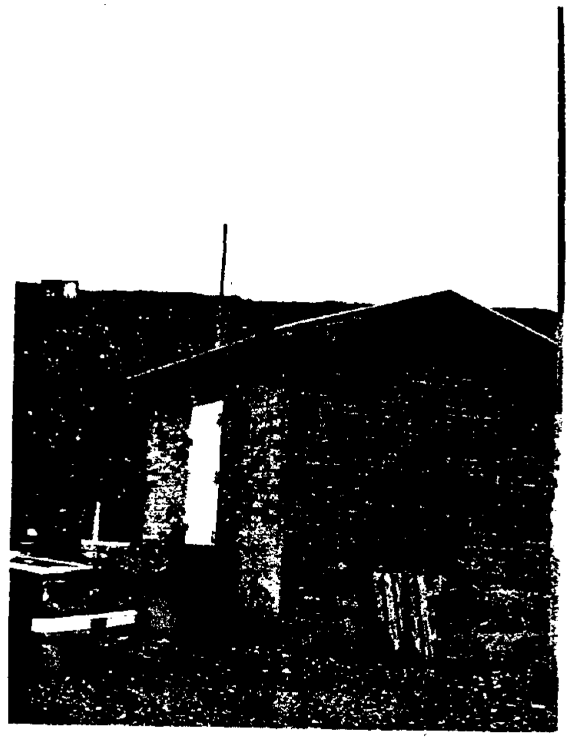

Fig. 3c. Two-Mast System - Close Spacing of Ground Terminals

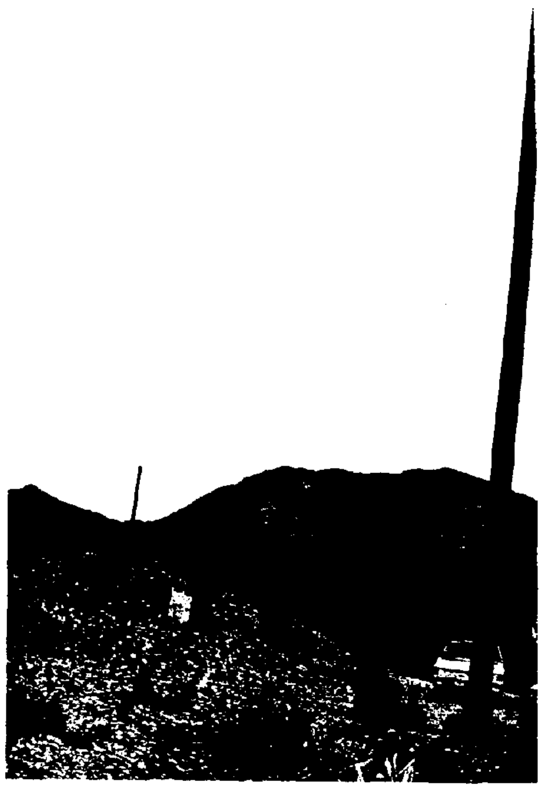

Fig. 3b. Two-Mast System - Wide Spacing of Ground Terminals

Fig. 3. LIGHTNING "PROTECTION" SYSTEMS FOR MAGAZINES

hazard. To intercept a stroke, air terminals should be close to the "protected" structure but this invites side-flashes to the structure through the air, or more probably along the ground. Thus, a compromise is required in the location of the system. To eliminate side-flashes, the ground terminals of the systems must be capable of rapidly dissipating the electrical energy of the stroke. This requires a good ground of the order of 10 ohms or less. A simple stake driven into Arizona soils or rock will not attain the low resistance necessary. To make the Arizona system more effective will require that air terminals be connected to ground terminals consisting of a buried grid network, or at least to a large buried wire loop around the structure to be protected. For greater interception capability, criss-crossing overhead wires are necessary. Such installations are costly and in view of the expected very low frequency of lightning-generated explosions they do not appear to be economically viable. It makes more sense to accept this low frequency risk and protect personnel and property by appropriate magazine siting and by ensuring that personnel be kept away from magazines during electrical storms.

5.4 Sympathetic Detonations

Even though magazine explosions are rare it is very poor practice (and illegal) to locate magazines close to inhabited buildings (on or off mine property), to public highways, and to each other. An improperly sited magazine is a potential projecticle and blast <u>hazard</u> to personnel and property. Proper separation distances must be based on the American Table of Distances. A remarkable validation of the American Table of Distances was described in Section 4.1.

Several apparent violations of the Table of Distances are presented in Table 10. At seven operations that we visited, magazines appeared to be too close to inhabited buildings on mine property. Three of these apparent violations were observed at quarries, two at surface coal mines, one at an underground coal mine, and one at an underground Ag/Au mine. At one of the above three quarries, magazines appeared to be also too close to a public highway.

Locating magazines close together obviously increases the risk of sympathetic detonations. Our observations of <u>intermagazine</u> separation and compliance or non-compliance of these separations with the American Table of Distances are summarized in Table 17. Although no serious violations were noted, at four mines explosion of the HE magazine would probably

Table 17. Inter-Magazine Distances and Compliance With American Table of Distances

	Approx. Distance (Ft)		Am. Table of Distances	
	HE to Deton.	HE to BA*	HE to Deton.	HE to BA*
Surface Coal A	50	100	(a)	OK
B	50	200	(a)	OK
C	300	Large	OK	OK
D	70	2000	OK	OK
E	75	Large	OK	OK
F	(b)	(b)	(b)	(b)
G	200	1700	OK	OK
H	50	250	(a)	OK
I	200	600	OK	OK
Underground Coal J	100	N/A	(c)	N/A
K	250	N/A	OK	N/A
L	100	N/A	(c)	N/A
M	200	N/A	OK	N/A
Surface Cu N	150	Large	OK	OK
O	300	N/A	OK	N/A
Underground Cu P	8000	N/A	OK	N/A
Q	300	N/A	OK	N/A
Underground Ur R	200	N/A	(c)	N/A
Underground Ag/Au S	1000	N/A	OK	N/A
T	500	N/A	OK	N/A
Surface Ag/Au U	150	N/A	(a)	N/A
Taconite V	200	N/A	OK	N/A
W	25 (d)	N/A	(a)	N/A
X	100	N/A	(a)	N/A
Y	50	N/A	(a)	N/A
Z	200	N/A	OK	N/A
AA	100	N/A	OK	N/A
Quarries AB	25	N/A	(a)	N/A
AC	400	N/A	OK	N/A
AD	100	N/A	(c)	N/A
AE	200	300	OK	OK
AF	150	4 (e)	(a)	(a)
AG	100	250	OK	OK (f)
AH	100	250	OK (f)	OK (f)

* N/A means no BA storage or no <u>separate</u> BA magazines; could have AN-FO storage bins but all of these are far removed from explosives magazines.

(a) Explosion of HE magazines expected to create an explosion of detonators in detonator magazine, but not vice-versa.

(b) No data.

(c) Same as (a) but number of detonators in detonator magazine exceeds 10,000.

(d) Several magazines closely grouped in a fenced area.

(e) Counted as a single magazine.

(f) Borderline.

produce the explosion of a large number of detonators in detonator magazines that were located too close to the HE magazines. In an additional nine instances, explosion of the HE magazine would be expected to explode a considerably smaller number of detonators, not because the separation distances were more acceptable, but just because fewer detonators were stored in the detonator magazines. In no case would the explosion of a detonator magazine be expected to explode the HE magazine. Quarries again appeared to have more questionable magazine sitings than other operations, although, surprisingly, this problem was also noted in taconite mines which are usually very safety-conscious. All observed HE to BA magazine separations appeared to be in compliance with the American Table of Distances.

5.5 Flammable Atmospheres in AN-FO Drop Trailers

It is conceivable, and even likely, that a prolonged hot spell can generate a combustible atmosphere in an unventilated AN-FO drop trailer. After all, the flash point of No. 2 fuel oil (the FO in AN-FO) is around 125°F, and temperatures inside a trailer can readily exceed this range when ambient temperatures are of the order of 100°F. Such a combustible atmosphere is a distinct fire hazard in the presence of lighted cigarettes or electrostatically generated sparks. Other additional trigger mechanisms can be lightning. Typically, drop trailer walls or roofs are about 1mm-thick (30 mils) aluminum. Moderately intense lightning strokes can penetrate such thicknesses and possibly ignite the combustible atmosphere on the inside. In favor of this scenario, it should be noted that drop trailers are good targets for lightning strikes. Their dimensions are relatively large and they are frequently parked "in the open". Furthermore, thunderstorms are more frequent in hot weather which is also conducive to the creation of a combustible atmosphere inside a trailer. It should, however, be noted that there are no recorded fires of the type described above.

6.0 COMPARISON OF EXISTING STANDARDS AND RECOMMENDATIONS ON EXPLOSIVE STORAGE

Several Federal agencies, most states, and even some local government entities issue standards or regulations on the storage, transportation and use of explosives. With so many regulatory agencies involved, it is not surprising that there is inconsistency and even contradiction in some of the regulations. Furthermore, IME distributes a set of recommendations, which although not legally binding, have wide circulation. These IME regulations do not agree in all respects with several Federal standards, but then there is as much disagreement among the Federal standards. In what follows, the discussion will be largely confined to Federal standards on explosive storage with some comparison of Federal standards with IME recommendations and state regulations. Since this study is concerned primarily with explosive storage on mine property, most of the following discussion will deal with the comparison of MSHA standards with other regulations and recommendations.

Directly applicable to the storage of explosives on mine property are MSHA and BATF standards and IME recommendations. OSHA regulations do not apply to storage on mine property but some of these will be examined for comparison purposes. DOT regulations apply only peripherally inasmuch as both MSHA and to some extent BATF use DOT definitions of "Explosive" and "Blasting Agents."

In essence, MSHA standards are primarily directed to conditions and practices to be observed in explosive storage, while BATF regulations address magazine construction and safeguarding against unauthorized entry into magazines. OSHA standards cover about the same ground as MSHA and BATF standards but they are not as comprehensive. IME recommendations cover subjects addressed by both MSHA and BATF.

MSHA standards are contained in CFR (Code of Federal Regulations) 30, "Mineral Resources". These are divided into standards applicable to metal/nonmetal mines and standards for coal mines. They are further subdivided into standards for open pit operations (subchapter N, part 55, paragraphs 55.6-1 through 55.6-20); sand, gravel and crushed stone operations (part 56, pargraphs 56.6-1 through 56.6-20); and underground operations (part 57, paragraphs 57.6-1 through 57.6-31) for metal/nonmetal mines. Except for three additional standards (57.6-27, 57.6-29, 57.6-30) for underground mines, these three sets of standards are identical. The standards for coal are separate for underground storage and above-ground storage. The former are contained in part 75 - Mandatory Safety Standards - Underground Coal Mines (subpart N, paragraphs 75.1306 and 75.1307) while the latter are in part 77 - Mandatory Safety Standards, Surface Coal Mines and Surface Work Areas of Underground Coal Mines (subpart N, paragraphs 77.1300 and 77.1301). The storage standards for surface coal mines are much more detailed than those for underground coal mines but they are not as comprehensive as those for metal/nonmetal mines. The surface coal standards do not contain the equivalent of metal/nonmetal standards 55.6-6, 55.6-7, 55.6-11 and 55.6-12. The first of these "omitted" standards pertains to combustile material around magazines; the second to first use of the oldest stock stored; the third to closing storage containers; and the last to the removal of explosives before a magazine is repaired. Furthermore, there is a minor disagreement between metal/nonmetal and coal standards. Paragraph 55.6-7, item d, permits stacking of explosive containers up to a height of eight feet while paragraph 77.1301, item g, states that cases may be stacked to a height of up to six feet.

Neither set of current standards on explosive storage explicitly forbids smoking or open flames in or around storage magazines. For metal/nonmetal, standards such as 55.6-250 forbid smoking around magazines indirectly. Even less direct or specific is coal standard 77.1711: "No person shall smoke or use an open flame where such practice may cause a fire or explosion."

The latest set of BATF standards that we examined was contained in the Federal Register of Friday, August 7, 1981, Part II, Department of the Treasury, BATF, "Recodification and Amendments to Explosive Materials Regulations", pp. 40382-40411. As already stated, BATF standards are primarily directed towards: magazine construction, record-keeping, and prevention of unauthorized entry. Specifications for magazine construction are considerably more explicit and detailed than the corresponding MSHA standards. BATF standards differentiate between mass-detonating and non-mass detonating detonators.* There is no such distinction in the MSHA standards. BATF standards (Fed. Reg. 46, August 7, 1981, paragraph 55.213) permit storage of safety fuse with non-mass-detonating detonators. MSHA standards are not specific on this subject but imply that safety fuse is to be stored with explosives (e.g., paragraph 57.6-8).

Similarly, BATF standards are more specific than MSHA standards with regard to magazine ventilation. Paragraph 55.214, item a (BATF), specifies lattice work, etc. inside a magazine to

* Some preliminary results at PRC suggest that differentiation between mass-detonating and non-mass-detonating electric blasting caps is not as clear-cut as was originally thought.

prevent placement of explosive directly against magazine walls (examples of this are to be seen in Figure 2d). MSHA requires "adequate ventilation" without stating how this is to be achieved (see e.g., 57.6-20, item g).

OSHA standards for explosive storage are contained in 29 CFR 1910, OSHA 2206 (revised June 1981), pp. 216-220. They address storage practices as well as magazine construction but are generally less detailed than MSHA standards for the former and BATF standards for the latter.

An OSHA standard that in principle is to be recommended is the requirement for storing recovered misfired explosives in a separate magazine until they are safely disposed. In practice, few mines have extra magazines for such storage and misfired explosives are hopefully shot or burned soon after recovery.

Recommendations by IME concerning explosive storage are contained in IME Publication No. 3 (1980) and Publication No. 1 (1977). The latter deals with magazine construction and is more detailed than the BATF standards in that it presents actual plan-drawings and details for such items as foundations, vents, door latches, etc. It also lists a minimum ventilation area, namely 0.2 square inches per cubic foot of magazine space. Publication No. 3 closely follows BATF standards. It does define "bullet-resistant" which is not defined in the BATF standards referenced above. Questionable and disturbing is the listing of electric blasting caps under "low explosives". Along similar lines, Class C explosives (which include limited quantities of detonators) are said to be of "minimum hazard." Detonators are the most sensitive explosives used in mining. Thus listing them under "minimum hazards" seems inappropriate. Also problematic is the recommendation to store recovered misfired explosive in "a magazine", <u>not a separate</u> magazine, until they can be safely disposed.

We shall present for comparison only two state regulations that are more specific than Federal standards. The California Administrative Code Title 8, Industrial Relation, Chapter 4, Division of Industrial Safety, Subchapter 17, Mine Safety Orders (1974) requires that magazine be placed <u>at least</u> 25 feet away from low-voltage power lines and <u>at least</u> 100 feet away from high-voltage power lines. This is considerably more specific than MSHA's "<u>away</u> from power lines" and consequently less subject to "judgement calls" by inspectors. The Mining Code of the State of Arizona, 1980 Revised Edition, requires that: "Magazines shall <u>not</u> be grounded, but have an overhead <u>lightning protection</u> system that is in no way connected to the magazine." The no-grounding requirement contradicts MSHA's standard for grounding metal magazines, and none of the Federal standards require lightning protection.

7.0 CONCLUSIONS

The stated purpose of the present study is to increase the safety of explosive storage. This was accomplished by:

- Review of the histories of recent and past magazine explosions (7.1);

- Observation of present-day explosive storage conditions and practices at a variety of active mines (7.2);

- Examination of existing Federal regulations pertaining to explosive storage to determine whether they address all conceivable safety problems, whether they contain redundant or obsolete standards, and whether their intent is clearly stated (7.3);

- Recommendations for safety improvements and for revision and clarification (if necessary) of governmental regulations (8.0).

7.1 Explosion Histories

Magazine explosions are rare. In the past decade, there were roughly 10, but only about seven per decade for the period 1884 to 1926. This apparent increase in magazine explosion frequency must be attributed to a large increase in deliberate (criminal or malicious mischief) explosions. During the 1970-1980 decade there were six such explosions while over the forty-plus years of 1884-1926, there were only <u>three</u>. Unfortunately, there appears to be little that can be done to eliminate this hazard.

Fires of various origins account for the remaining four explosions of the past decade. Fire was also a major hazard in the 1884-1926 period, but so was <u>lightning.</u> It is noteworthy that all these lightning-generated explosions occurred in <u>non-metal</u> magazines.

The potential hazards created by a lightning stroke upon an explosive magazine were examined in considerable detail. It is concluded that the contents of a well-constructed, <u>metal</u> magazine are immune to direct lightning strikes, <u>regardless</u>

This applies to magazines with 40-mil-plus metal sheeting as well as all-metal magazines.

whether the magazine is grounded or not grounded. Grounding a metal magazine cannot be harmful, but it may well be superfluous and come under the category of "guilding the lily". For non-metal magazines, the risks of a lightning-generated explosion cannot be ignored. Statistical analysis applied to considerations of the mechanisms of lightning strikes and explosion trends (in the 1884-1926 period) suggest that there is a high probability of one lightning-generated explosion of a non-metal magazine in a 15-year period. Effective lightning-protection systems should minimize this frequency, but in view of the already low frequency the cost of implementing an effective system does not appear to be justified except in special cases.

It should be emphasized that fires initiated by nearby lightning strikes did result in the explosion of two magazines in the last ten years. For this and other reasons, it is imperative to keep areas around magazines clear of combustible materials.

Hazards of electrical origin (other than lightning) appear to be quite remote. There are no recorded instances of magazine explosions or fires caused by electrical power lines or by static electricity.

Although not specifically proved, combustible fuel/air mixture may develop in unventilated AN-FO drop trailers during hot weather. In combination with a lightning strike (also more likely in hot weather) which penetrates the thin wall or roof of a drop trailer this could be a hazard. Of course, other ignition sources such as lighted cigarettes, static or friction sparks, etc. can make this combustible atmosphere a fire hazard. (See Section 8.1.5).

7.2 Mine Visits

Magazines were observed at 34 widely separated mines and storage problems were discussed with personnel at these mines. In general, storage conditions and practices were found to be satisfactory. Some of the shortcomings observed were: combustible materials around magazines, improper magazine sitings, overloading (one instance only), and non-explosive items that should not be stored in magazines. In most cases, "sloppy" practices were found in magazines at very small mines and/or at mines where contractors handled all explosive operations.

It is very noteworthy that few explosives are usually stored on mine property. At many mines, most explosives are brought in as needed by suppliers. Thus, large concentrations of explosives are to be found in supplier magazines. These were not examined during the present study. Consequently, this study addressed only the "tip of the iceberg", as far as explosive storage is concerned.

7.3 Federal Regulations

MSHA and BATF standards on explosive storage were examined from the point of view of adequacy (with regard to safety) and clarity (with regard to complaints by the mining community about inconsistency of enforcement of these standards). Safety problems, with the possible exception of lightning hazards, were found to be adequately covered. Problems of clarity and recommendations for their improvement will be considered in Section 8.0.

8.0 RECOMMENDATIONS

The following discussion will be divided into three subsections; the first dealing with safety aspects, the second with modification of existing standards and enforcement of these standards, and the third with suggestions for further study. In general, relatively little needs to be done to enhance storage safety, but government standards concerning explosive storage and their enforcement contain problem areas that need improvement. Care will be exercised to emphasize changes that are economically viable and stand a good chance of compliance from the mining community.

8.1 Safety Improvements

The five areas considered are: deliberate explosions; fires; magazine siting; lightning and grounding; AN-FO fumes. A brief general discussion on reducing the risk of these hazards will be followed by suggestions on what additions or modifications might be made in current MSHA standards.

8.1.1 Deliberate Explosions

Little can be done to prevent a determined criminal from blowing up an explosive magazine. Aside from keeping magazines locked and free of combustibles around them, there are few, if any, viable preventive measures. It may be desirable to specify the degree of bullet resistance (as for example in IME Publication No. 3) in the MSHA standards rather than the presently used "reasonably bullet-resistant". Obviously, it is totally impractical to require that magazines be resistant to all types of projectiles (armor piercing, shaped charges, etc.). As far as "pranks" or malicious mischief are concerned, education of youngsters as to the great danger of tampering with explosive magazines can be helpful. This can be in the form of posters or brief talks provided to schools, Boy Scout meetings, etc.

8.1.2 Fires

Fires, not deliberately-set, in and around magazines can be prevented. The obvious safe-guards of keeping the areas around magazines clear of combustibles and the use of incombustible materials in construction are adequately covered in existing MSHA standards. Somewhat less adequate are the standards on flame-producing devices near or in magazines. The standards on removing explosives from a magazine prior to its repair address this subject. Also, there is a prohibition against smoking, etc. near explosives, but this standard is not very specific as to explosive magazines, and in CFR 30 it is placed in "left field", far removed from the standards that address explosive storage. It is recommended that the non-smoking, no-flames requirement be moved back to the storage section where it used to be in the 1978 and prior MSHA standards.

8.1.3 Magazine Siting

Existing standards are quite clear on this subject. However, our observations suggest that these standards are sometimes violated, since magazines appear to be too close to each other or to "inhabited buildings" etc. Clearly, this is a matter for stricter enforcement rather than modification of existing regulations.

8.1.4 Lightning and Grounding

Lightning, its effects and protective measures against it are not addressed in any Federal standards on explosive storage. Grounding of metal magazines now required by MSHA is a subject of considerable controversy. It is the conclusion of the present study that metal magazines are immune to explosions directly generated by lightning.* Thus, there is no need for any new MSHA standards on this subject. There is, however, a high probability that non-metal magazines can be shot by lightning, but this is expected to be a very infrequent event. Special danger areas of non-metal magazines are metal roofs or metal doors. They should be bonded together and grounded. Even a high-resistance ground (kilo-ohms or even megohms) will greatly reduce the hazard posed by such electrically charged but otherwise insulated conductive regions. In these magazines, explosives should be stored as far as possible from metal roofs or walls to minimize the potetial hazard of side-flashes.

As to the grounding of metal magazines, it is not harmful nor particularly helpful. In view of the frequent citations of "inadequate" grounding systems (since they do little if anything to enhance storage safety), it would be a boon to the mining community if this standard were deleted.

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* Provided these magazines do not contain electrical fixtures, which is the case for the vast majority of present-day magazines.

8.1.5 AN-FO Fumes

It is likely, indeed probable, that appreciable quantities of fuel oil vapor will exist in unventilated AN-FO drop trailers during hot weather. This can be a health hazard and even a fire hazard if the temperature inside the trailer exceeds the flash-point of No.2 fuel oil (about 125°F). Ignition sources for such a combustible atmosphere can be lighted cigarettes (unfortunately people do smoke in and around AN-FO trailers), static sparks generated by personnel moving around inside the trailer, friction sparks, or lightning strikes puncturing the thin walls or roof of the trailer. Appropriate ventilation should minimize this hazard. However, this may not be easy to achieve. Frequent (possibly daily) opening of the side doors and back door (if there is a back door) during hot weather should be helpful. It would be advisable to touch a bare grounded metal wire to the trailer wall prior to the opening of the doors to ensure that the trailer does not have an electrostatic charge. This also removes any static charge from the person. Of course, this procedure is unnecessary if the trailer is already grounded (e.g., via a metal jack).

8.2 Modification of Existing MSHA Standards on Explosive Storage

Three general areas will be considered in an effort to make existing MSHA standards even better than they now are; namely, additions, deletions and clarifications. Certain "grey" areas which require further study will be outlined in Section 8.3.

8.2.1 Additions

There appears to be some confusion about the storage of fuse lighting devices (ignitacord, pull-wire lighters, etc.). It is recommended that a new standard be added which states that it is preferable to store fuse lighters separately, but if this is not possible then store them in a detonator magazine.

There is a standard (e.g., 57.6-124) that requires personnel to be withdrawn to a safe location during the approach of an electrical storm. It would be desirable to broaden this standard to specify that personnel should not approach explosive magazines (particularly non-metal magazines) during an electrical storm or even for some time (say 15 to 30 minutes) after the passage of the storm.

For safety of personnel as well as prevention of possible explosions, it is recommended that a new standard require that metal parts of a <u>non-metal</u> magazine be bonded together and grounded.

In non-metal magazines that have metal roofs and metal doors, explosives should be stored as far as possible from the metal parts. If this recommendation is adopted, existing standards such as 55.6-7(d), allowing eight foot high stacks of explosive containers, may have to be modified.

To prevent the formation of a combustible atmosphere, a new standard should specify that doors of AN-FO drop trailers should be opened frequently (daily) during hot weather. Conversely, it could be required that all An-FO drop trailers have ventilation systems. However, effective and viable systems will be hard to achieve.

8.2.2 Deletions

Since the grounding and bonding of metal magazines (standards such as 55.6-20(e)) is at best of marginal safety benefit, it is recommended that this requirement be made optional or deleted altogether.

Modern high explosives are relatively insensitive to friction sparks. Consequently, consideration should be given to deleting the requirement for non-sparking material on the inside of explosives magazines (standards such as 55.6-20(f)). This is still a "grey" area and will be addressed further in Section 8.3.

8.2.3 Clarifications

Existing standards are not entirely clear about storage of detonating cord or safety fuse (e.g., 55-6-8). It is desirable to state clearly that detonating cord and safety fuse must be stored in explosive magazines, unless MSHA is willing to permit storage of safety fuse in detonator magazines as well.

Prohibition of smoking and flames in and around magazines is implied by standards such as 55.6-250 or 77.1711. It is recommended that this prohibition be made more explicit and be included in the sections dealing with explosive storage.

The major complaint of the mining community concerns the lack of consistency in MSHA inspection of magazines and enforcement of MSHA storage standards. Some of this inconsistency can be eliminated if certain existing standards were made less vague. With this in mind, it is recommended that:

1. For standards such as 55.6-12, include language such as: "...removed at least as far from the magazine under repair as required for that amount of explosive by the American Table of Distances for intermagazine separation". This is to be used instead of the present wording of "safe distance".

2. For standards such as 55.6-20(b), delete "...away from power lines" and substitute "...at least as far removed from power lines as the distance between supports of the power line".

3. For standards such as 55.6-20(d), include language to define "reasonably bullet-resistant"; e.g., the definition IME Publication No. 3.

4. Explosive storage standards for metal/non-metal be made consistent with the standards for coal. Differences between these two sets of standards were summarized in Section 6.0.

An additional instrument to enhance inspection consistency is a regularly scheduled free-wheeling discussion of standards, inspection procedures, and problems at each MSHA office. Surely, it is impractical and undesirable to make the standards so detailed as to stifle any lee-way that may be dictated by local conditions. On the other hand, too many "judgement calls" by the inspectors are just as undesirable. Discussion meetings can go a long way to creating a happy medium. It is our understanding that at least one MSHA office already follows this approach.

8.3 Future Studies

The superintendent of a quarry that we visited felt very strongly that <u>all</u> Federal standards pertaining to explosive storage (and possibly transportation) should be included in a booklet of a few pages. Similar thoughts, though not as explicitly stated, were voiced by other members of the mining community. Such a booklet would also be of benefit to Federal inspectors. It is believed that a prototype booklet can be developed in a relatively minor effort and submitted for review to the agencies concerned and possibly to IME and to selected mining personnel.

In Section 7.0, it was pointed out that the present study covered only the "tip of the iceberg" as far as explosive storage was concerned, since most explosives are stored not on mine property but at supplier's or distributor's magazines. A study similar to the present one, but restricted to magazine visits, discussions with personnel at these magazines, and discussions with explosive manufacturers should be undertaken. Such a study will indicate where large quantities of explosives are located, under what conditions they are stored, and the problem areas that exist. It is realized, of course, that supplier magazines are under the jurisdiction of OSHA and BATF. However, since the driving force behind such a study is increased safety, it would be desirable to carry out such a study possibly as a cooperative effort by the agencies involved.

Whether only non-sparking materials should be required inside magazines is a kind of "grey" area. Certainly, the existing standard on this subject cannot be faulted if it indeed addresses a real hazard. On the other hand, if this standard is primarily a carry-over from the days when black powder was extensively used, it is an unnecessary burden on the mining community. A review of what is known about the spark sensitivity of modern explosives should provide MSHA with the basis for deciding whether this standard should be retained, deleted or modified. Conceivably, a modified standard might delete this requirement for explosive magazines but retain it for detonator magazines (particularly those in which fuse caps are stored). A related subject that needs examination is the ignitability of combustible fuel oil/air mixtures by friction sparks. In other words, is it prudent to extend the non-sparking requirement to AN-FO drop trailers?

Another grey area is that of storage of mass-detonating or non-mass detonating explosives. First of all, the distinction between the two groups appears to be somewhat subjective and depends on what tests are used to classify the explosives and even on who does the testing. Secondly, there is no mention whatsoever in current MSHA standards of this distinction. BATF standards do recognize these two classes but do not specify on what basis the distinction is made. A review of this entire subject is badly needed. Such a review should concentrate on the analysis of existing data to determine whether there is an adequate basis for the mass-detonating and non-mass-detonating classification. In particular, data that distinguish these two groups for exposure to bullet impact and to fire should be emphasized since these appear to be the major hazards in present-day storage of explosives.

APPENDIX A

QUESTION LIST FOR MINE VISITS

1. IDENTIFICATION Date of Visit ____________

1.1 Type of Operation OP/_/ UG/_/ Q/_/ SG/_/

1.2 Mine Name & Location/Address ____________

1.3 Operator/Owner ____________

Address ____________

1.4 Product ____________

1.5 Waste Rock ____________

1.6 Average number of employees ______ Working ______ Shifts

2. TOPOGRAPHY & POPULATION

2.1 Nature of Terrain ____________

2.2 Nearest population centers ____________

2.3 Nearest non-mine housing ____________

2.4 Nearest highway or railroad ____________

2.5 Nearest other mining activity ____________

3. BLASTING PRACTICES

3.1 Main charge ____________

3.2 Loading of main charge: Bags/_/ Cartridges/_/ Pumped/_/ Augured/_/

3.3 Boosters ____________

3.4 Mode of Initiation: Blasting caps/_/ EB's/_/ Delay EB's/_/ Detonation Cord/_/ Nonel/_/ Other/_/ ______

3.5 On-site explosive mixing if any ____________

3.6 Explosive Consumption: Main charge ____ Boosters ____ Detonating cord ____ Detonators ____ Fuse & Lighters ____

3.7 Blasting schedule ____________

4. MAGAZINES

4.1 How many Explosive Magazines _____, Cap Magazines _____, Blasting agent stores? ______.

4.2 Total Storage, Explosives ____lbs., Caps _____ Blasting agents _____lbs.

4.3 Are there any "large" detonators in Cap Magazines? ________________________________

4.4 High explosives magazines are _____ft. from cap magazines

4.5 High explosives magazines are _____ft. from blasting agent stores

4.6 Inter magazine separation is ______ft. ____

4.7 Construction: ____

4.8 Approximate dimensions: ____

4.9 Are Magazines barricaded? Yes/_/ No/_/ Partially/_/

4.10 How far is it from the magazines to the nearest place where employees would usually be working? _______________ft.

4.11 To haulage roads __________ft. To Mill/crusher _________ft.

4.12 To offices _________ft. To nearest major installation ________ft. (______)

4.13 How far to the nearest highway or railroad? _________feet.

4.14 How far to the nearest inhabited building? _________feet.

5. SAFETY & SECURITY

5.1 Are explosives boxes stored closed? Yes/_/ No/_/

5.2 Is storage arranged so that the oldest stocks are used first? Yes/_/ No/_/

5.3 How often are explosives ordered? __________ times per year

5.4 How much care is taken to clean up grit contaminants and spilled explosive in the magazines?

Little Care __/__/__/__/__/__/__/__/__/ Scrupulous Cleanliness
1 2 3 4 5 6 7 8 9

5.5 Are there unnecessary tools or other items in magazines? ____________

5.6 Are areas around magazines free of fire hazard and rubble? ____________

5.7 Do magazines have lightning conductors? Yes/_/ No/_/

5.8 Is cap magazine electrically shielded

By metal exterior /__/ 1.
By grounded metal exterior /__/ 2.
By grounded metal exterior and lightning conductor /__/ 3.
Not shielded /__/ 4.

Nature of exterior ground ____________

5.9 Are stores for blasting agents

As fire resistant as explosive magazines /_/ 1.
Less fire resistant then explosive magazines /_/ 2.
Very much less fire resistant /_/ 3.
Missle protected from H.E. Mag /_/ 4.
As bullet resistant /_/ 5.
Less bullet resistant /_/ 6.
Very much less /_/ 7.

5.10 Do magazines have proper warning signs? ____________

5.11 Are areas around magazines fenced? ____________

5.12 Alarms if any for unauthorized entry? ____________

5.13 Type of locks ____________

5.14 Type of Ventilation ____________ Blasting Agent Storage Ventilated ____________

5.15 Type of Lighting ____________

5.16 Nature of Bullet resistance of H.E. Magazines: inches of ______ steel ______ wood ______ other

6. ACCIDENTS & INCIDENTS

6.1 Any explosion of magazines? ____________

6.2 Any potentially hazardous incidents? ____________

6.3 Any accidents or incidents during explosive disposal? ____________

6.4 How are deteriorated explosives disposed ____________

6.5 Who determines that explosives need to be disposed ______________________________

6.6 Fires in explosive trucks ________________________

7. INSPECTIONS

7.1 Who is responsible for magazine safety and security? ______________________________

7.2 Are there regular safety inspection of magazines? ________________________________

7.3 Number of MSHA magazine inspections ______________ during last _________ years

7.4 Number of MSHA citations for violations of explosive storage _________ during last _____ years

8. TRAINING OF PERSONNEL WHO DEAL WITH EXPLOSIVE STORAGE

8.1 Who is in charge of receiving and storing explosives? ______________________________________

8.2 Who orders additional explosive supplies? ____

8.3 Who is authorized to remove or return explosives? ____

8.4 Is there any training program for personnel dealing with explosive storage? ___________________

8.5 What type of program is used? ____

8.6 Is there a periodic update of training? ____

9. Additional comments, sketches and identification of photographs taken _________________________

____

____

APPENDIX B

SUMMARY OF COMMENTS OF MINING COMMUNITY ON STORAGE REGULATIONS AND INSPECTIONS

Mine A :	Questioned the necessity for locking ANFO storage bins.
Mine B:	Enforcement of storage regulations is inconsistent. Some OSM regulations should be eliminated and/or simplified.
Mine C:	Federal and State regulations should be consistent.
Mine D:	No comments.
Mine E:	No comments.
Mine F:	More explosives stored at distributor magazines than on mine property.
Mine G:	Inspections are inconsistent; ANFO bins not locked because locks corrode rapidly.
Mine H:	Inspections are inconsistent. Claim that some of DOT and MSHA regulations on transportation of explosives are at odds. Locks on ANFO bins corrode.
Mine I:	Find MSHA inspectors quite helpful.
Mine J:	No comments.
Mine K:	Hope that no additional regulations are forthcoming.
Mine L:	Claim that tension on 7.5KV powerline, which is about 30 feet above a magazine will pull it away from the magazine if the line breaks.
Mine M:	They are proud of their strict inventory control.
Mine N:	The first inspection by an MSHA is fairly thorough. Subsequent inspections by the same inspector are rather cursory. Non-sparking surfaces in magazines are a "pain" to implement and maintain. Keeping records on MSHA training of miners takes longer than the actual training.

See Table 5 for type of material mined

Mine O: No comments.

Mine P: Believe that original standards were just suggestions for good practices. Then "politics" put "some teeth into MSHA standards," even though no set of standards can be applied to all mining operations because conditions and practices vary so much from mine to mine.

"No practice can be absolutely safe. Some hazards though potentially disastrous have a very low probability of occurrance. It is ridiculous to spend thousands of dollars to minimize the occurrence of a $100.00 loss."

Mine Q: No comments.

Mine R: Unhappy with non-sparking surface requirement.

Mine S: Argument with State inspector concerning the location of an underground magazine.

Mine T: Would like to see MSHA standards on magazine construction. At present there are no such standards and no reference to BATF standards.

Mine U: No direct comments but complained about "sloppy" practices by contractor.

Mine V: Claims they have to attach about 2 feet of 40 grain/ft. detonating cord to Nonel Primadets prior to shot loading. Question arises as to where this detonator/detonating cord combination should be stored.

Mine W: Existing storage regulations are good but need clarification to reduce "judgement calls" by MSHA inspectors.

Mine X: Tops of some containers for delay connectors or Nonel are subject to damage and are hard to close. Subsequently standards such as 55/6-11 (keep explosive containers closed) might be violated.

Mine Y: No comments.

Mine Z: Questions concerning day boxes. Where are they required and must they be locked if attended.

Mine AA: No comments.

Quarry AB: No comments.

Quarry AC: Complained about "Judgement calls" by MSHA inspectors. Claims to have gotten contradictory answers from inspector and district office as to moving a magazine "away" from a power line.

Quarry AD: No real problems but inspectors tend to be inconsistent.

Quarry AE: Problems with MSHA about "concrete" lining of a converted trailer magazine (citation pending). Claims state inspector more competent than MSHA inspector. Complained about frequent MSHA inspections because of proximity of MSHA district office.

Quarry AF: No comments.

Quarry AG: Quarry superintendent claimed he had little control over magazines that belong to a contractor but are located at this quarry. Stated that existing regulations are ok.

Quarry AH: Would like all regulations pertaining to storage and transportation in one short document; not scattered through several large volumes issued by various agencies. Claims to be "overrun" by inspectors. Would like to see the "Feds run the whole show" so as to avoid confusion due to State and Federal inspectors disagreeing.

Explosive Distributor: Claims that transportation of explosives on public highways, to and from main magazines to temporary storage magazines is more dangerous than limited overnight storage in the temporary magazines even though location of the temporary magazine does not comply with the American Table of Distances.

APPENDIX C

STATISTICAL ESTIMATES OF ANNUAL LIGHTNING STRIKES ON PERMANENT EXPLOSIVE MAGAZINES

According to R. H. Golde ("Lightning Protection", 1975), if a "stepped leader", which is moving towards the earth from a thunder cloud, approaches a structure, of height H, within twice the structure height, the return stroke will be via the structure rather than directly through air. This is so because a wet non-metallic structure (and of course a metallic structure) is a better conducting path than a column of air of the same height. The area presented by a structure to an approaching "stepped leader"; i.e., the curved surface above the structure from which the distance to the structure is 2H, is given by:

$$A = LW + 4\pi H(L+W)/3 + 16\pi H^2/3$$

where L and W are structure length and width. Incidentally, this area is given by Golde as $A = LW+4H(L+W)+4\pi H^2$ which is close enough to the above more accurate formulation for structures such as magazines for which $L > W \approx H$.

Golde presents strong arguments in favor of the randomness of lightning strikes (no "lightning nests"). Thus any square kilometer of earth is as likely to be struck as any other square kilometer of similar contour and elevation. Consequently, the expected frequency of strikes on any structure is simply nA where n is the number of annual lightning strikes per square kilometer for the particular region (it depends on the number of thunderstorm days within that region) and A, the presented area of the structure, is expressed in $(km)^2$. For magazines in the U.S. (or for that matter for most structures), nA is a small number; i.e., a lightning hit on any single magazine is a very infrequent event. However, there are many magazines throughout the U.S. Such a combination of many targets, N, each of which is hit very infrequently and randomly will follow a Poisson distribution. Consequently, the expected yearly number of lightning strikes on magazines is:

$$\lambda = nNA$$

and the probability that λ lies within prescribed limits is readily evaluated if $\lambda \geq 5$, since one can then transform the Poisson distribution into a normal distribution as follows: Let X_2 and X_1 be the upper and lower limits of λ. Define $t_2 = (X_2+1/2-\lambda)/\lambda^{1/2}$ and and $t_1 = (X_1-1/2-\lambda)/\lambda^{1/2}$. Look up F(t) for t_2 and 1-F(t) for t_1 in a Table of Ordinates and Areas of Normal Distribution. The probability, p, that λ lies between X_1 and X_2 is then given by

$$p = F(t_2)-(1-F(t_1)).$$

In section 5.3.3 (and in particular for Table 16), we needed to estimate the fraction of magazines that are "out in the open". This estimate had to be based on observations of a tiny fraction of the total magazine population. However, the observations were random in that they were made in widely separated locations and included different mining operations. Included in the observations are some data obtained in our study of blasting practices in surface mines (Contract No. J0366017), and, of course, the data collected in the present study.

First let us examine our observations of coal mine magazines. The magazines of all 13 mines that we viewed were judged to be out in the open. According to the statistical methods given by M.G. Natrella, NBS Handbook 91 (1963), p. 72, paragraph 7-3.1.1, this sample leads to the conclusion that, at a 95% confidence level, the proportion of the total coal mine magazine population which is "out in the open" lies between 0.775 and 1. In other words, we have high confidence that most above-ground coal mine magazines are "out in the open".

Similar reasoning, based on our observation that 29 of 36 magazines at all kinds of mines were out in the open, leads to the conclusion that at a 90% confidence level the proportion of all magazines that are out in the open lies between 0.69 and 0.91. Thus, on an average, the fraction of all above ground magazines that is "out in the open" is expected to be about 0.8.

During the present study and the surface mine study, we observed that 13 of 47 or about one-quarter of all magazines viewed were of the non-metal variety. Guesstimates of the fraction of non-metal magazines made by several outside sources ranged from one-third to one-half, but with everyone agreeing that this fraction is constantly decreasing. Applying the above statistical method to our observations, we find that at a confidence level of 90% the proportion of all magazines that are non-metal lies between 0.17 and 0.39.

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* Any structure that is covered by metal will be considered to be a "metal" magazine.

APPENDIX D

"IMMUNITY" OF METAL MAGAZINES TO LIGHTNING-GENERATED EXPLOSION OF THEIR CONTENTS

If lightning strikes a metal magazine what can happen to the explosives stored in the magazine? We will anticipate the answer about to be formulated in the analysis below, by stating that most probably nothing happens to the explosives. In other words, explosives stored in well-constructed, metal magazines are immune to direct lightning hazards. There is, of course, the indirect hazard of a nearby lightning-generated fire engulfing a magazine and exploding its contents (see Table 12).

There appear to be two possible mechanisms by which lightning might affect explosives stored on the inside:

1. Extensive heating of the roof or walls possibly followed by ignition of the internal structure (e.g., wood spacers) and/or explosives or explosives containers.

2. Puncture of the roof or walls with arcing inside the magazine.

Since there can be no electric fields inside the magazine (Faraday cage effect), the "usual" induction problems do not arise, nor is the very short-lived electromagnetic induction effect expected to be dangerous. Because explosives inside a magazine are not grounded, there can be no "side-flashes" from the magazine to the explosives.

Let us first examine the roof/wall heating mechanism. A conservative estimate of the cross-section, q, of the lightning path through a steel magazine wall is $1 \times 100mm^2$ (1mm corresponds to a wall thickness of about 40 mils and 100mm is a small fraction of the smallest wall dimension which is of the order of 3000mm). Now take the "action" intergral $\int i^2dt$ to be $10^7 amp^2 sec$ which is close to the highest level observed. Then the quotient $\int i^2dt/q^2$ is $10^3 amp^2 sec/mm^4$ which corresponds to a temperature rise of 60°C for steel and about 250°C for "corrosion-resistant" steel (from figure 8 of R. H. Golde's "Lightning," Vol. 2, 617 Academic Press, 1977). Surely, the former creates no problems, and even the 250°C appears safe since its duration will be short, and most likely, it is a gross overestimate since the cross-section was under-estimated while the action integral was overestimated. Thus, roof/wall heating by a lightning stroke is not expected to be a hazard to the contents of a metal magazine.

Conditions for roof/wall puncture are at present still ill-defined, because of complications introduced by the effects of duration of the lightning strike. According to Golde ("Lightning Protection," Chemical Publishing Co., NY, 1975, pp. 53-54, Fig. 26), even less than 20-mil metal sheet will not be punctured by the most severe strokes if stroke duration is around 1msec. For durations of the order of 4msec (only observed in rare positive flashes), at near maximum observed charge (≈ 400 coulombs), 1mm-thick metal sheets may be punctured but certainly not 2mm-thick sheets. Thus, for common short-duration negative flashes and usual roof/wall thickness (greater than 1mm), puncture is unlikely.