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**Safer Blasting Agents and Procedures for
Blasting in Gassy Non-Coal Mines**

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ABSTRACT

Gas and dust ignitions following blasting operations in underground non-coal mining operations have caused fatalities, serious injuries, and/or significant equipment and production losses. The U.S. Bureau of Mines has been involved in a long-term program to identify and reduce the frequency of fires and explosions during blasting operations in non-coal mines. The latest research, partially funded by this Interagency Agreement with the U. S. Department of Energy, focused on development of safer explosives and procedures for blasting in the presence of flammable gases and/or combustible dusts.

Hundreds of tests had been conducted in the Bureau's Lake Lynn Laboratory Cannon Gallery to evaluate the incendivity characteristics of both commercially available and experimental explosive products. The cannon gallery test results have clearly identified several lower incendive explosives that can and have significantly reduced the gas and/or dust ignition hazards associated with blasting in non-coal mines. Several of the lower incendive explosive formulations have undergone full-scale field evaluations and, to date, had been very successful in preventing ignitions in base metal mines with high sulphur-bearing ore. Tests in the cannon gallery have shown that an inert gelled water material outperforms most other stemming agents in preventing the ignition of flammable gases and/or combustible dusts outside of the bore. A new water stemming plug was evaluated in the cannon gallery and shown to be a very effective stemming device.

As a means to better evaluate explosive incendivity, the initial development of two instrument sensors are underway. A fiber optic rate probe has been redesigned to accurately measure the detonation velocity of explosives in the cannon bore. A photometric sensor is also under development to measure the peak temperatures of the detonation products exiting the bore.

This report discusses the results of the research program including the test apparatus and procedures and summarizes the incendivity data obtained from the various explosives. Results from the full-scale field testing of the lower incendive products in an operating mine are then presented.

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INTRODUCTION

BACKGROUND

The U.S. Bureau of Mines (USBM) Fires and Explosions Group in Pittsburgh, Pennsylvania, started a research program to develop safer explosives and blasting procedures for blasting in gassy non-coal mining conditions.

The USBM has been involved for many years in defining the hazards associated with the mining and processing of oil shale. Full-scale face blasts have been monitored in several western United States oil shale mines to measure dust generation and methane release rates. Extensive laboratory and experimental mine tests have also been conducted to determine minimum explosible oil shale dust concentrations for flame propagation with and without added methane and to evaluate the performance of various inhibitors in preventing ignition (1,2)¹. Although our knowledge of dust generation and methane release is incomplete, enough is known to outline the nature of the blasting hazards posed by the presence of these two potentially explosible substances. From research studies (1-4) conducted over the past several years relating to the dust problem, we know that:

1. Higher grade oil shale dust is flammable. Under certain conditions a combustion wave of explosive violence can propagate through a cloud of oil shale dust. This has been demonstrated in both laboratory-scale experiments and in the Bruceton Experimental Mine.
2. The dust can be ignited by chemical energy sources such as electric matchheads, burning methane, or blasting explosives including ANFO. However, owing to the high inert content it is noticeably more difficult to ignite than some other flammable dusts, such as bituminous coal.
3. The lower concentration limit for explosibility of oil shale dust in air depends on the kerogen content; shales with low kerogen content appear to be incapable of sustaining the propagation of a combustion wave.
4. The lean explosibility limit of oil shale dust in air is lowered by the addition of methane.

In relation to the methane problem, we know that:

1. Oil shale contains methane in amounts which depend on the nature and location of the deposit, i.e., depth and proximity to the outcrop.
2. Oil shale is relatively impermeable, and the natural release of methane is a slow process. However, at some mining locations, methane can apparently be readily liberated during blasting.

On the basis of these observations, underground blasting operations could

¹Italic numbers in parentheses refer to items in the list of references at the end of this report.

result in the initiation of ignitions involving methane and/or dust generated during the fragmentation process. These ignitions could, in turn, initiate dust explosions which could propagate in the main entries of the mine if sufficient dust of right grade and size distribution were present. Preliminary surveys of the dust generated and deposited during oil shale mining operations indicate that the average dust loading in an entry may be too low to support the propagation of an explosion over the entire length of an entry (3). Nevertheless, the possibility of violent explosions occurring in higher dust concentrations near the face has to be considered.

Although the occurrence of face ignitions has not yet been observed in oil shale mines, they are relatively common in sulfide ore mines and could be very destructive in oil shale mines because of their size. Over the past decade there has been a significant increase in the number and severity of blast-induced dust ignitions in the underground workings of metal/nonmetal mines (primarily the massive sulphide ore deposits) in Europe, South Africa, Australia, Canada, and more recently in the United States of America (5-8). Fortunately, the number of fatalities associated with these ignitions has been minimal due to the practice of evacuating mines before blasting. Even with minor ignitions, there is appreciable lost production while a mine is checked for toxic levels of sulphur dioxide, hydrogen sulphide, and other gases and the damage to the ventilation system is repaired to safely purge the mine of these toxic gases.

An informal survey of gassy non-coal mines such as trona and potash shows that, in general, the blasting practices to be based on extensions of the safety procedures used for shooting coal in underground mines. For underground coal ordinarily, charge holes are drilled with diameters being 5 cm or less, short delay electric detonators with copper shells are used, stemming is required, and the total quantity of explosives is limited. Certain "approved" blasting agents as well as permissible explosives are allowed and the use of slow delays is sometimes permissible. However, even this kind of "permissible" blasting practice is still inappropriate for producing oil shale and/or other non-coal products in the quantities needed to meet economic restraints.

Ammonium nitrate - fuel oil (ANFO) is the blasting agent of choice for use in the non-coal mining industry, including oil shale, sulfide ore and salt. However, it is well known that unstemmed charges of ANFO can easily ignite the flammable gas or combustible dust found in these mines. These ignitions occur when fine particles of dust or flammable gases are ignited. In underground mining, the energy required to ignite these dust clouds or gas concentrations are supplied by the explosives used in development and production blasting. Along with the useful work energy derived from the detonation of the explosives, large quantities of high temperature gas and hot particles of unreactant material are released. Blasting operations also generate large quantities of dust within the blast zone. The heat available in the afterburning of hot detonation by-products provides an energy source capable of igniting the predispersed dust and/or concentrations of flammable gas. In non-coal mine operations, the destructive pressures generated from a dust or gas ignition are generally limited to the blast face area and, in most cases, do not extend significant distances into other areas of the mine due primarily to the lack of sufficient fuel and dust dispersion. Blasting techniques for preventing gas and dust ignitions are well known in coal mining; they include the use of charges of permissible explosives in small diameter (5.0 cm or

less) boreholes with prescribed stemming, hole spacing, and delay timing. These coupled with the practice of generalized rock dusting, to render the loose coal dust nonflammable, and close control of methane levels have all but eliminated blasting-related coal mine explosions. However, it is generally considered that coal mine blasting practices, per se, are not applicable for producing oil shale in the quantities or at the rates necessary to make the recovery economically feasible. Recent work at the USBM has led to the development of explosive compositions and stemming materials that are considerably safer to use in potentially flammable atmospheres (9-11). In addition, studies of the detonation characteristics of these new explosives, including their gaseous products of detonation, indicate that their incendivity in gas or dust may be predicted on the basis of these characteristics, thereby supporting the development of even safer explosives (10).

The USBM has the only facilities and necessary expertise for conducting full-scale dust and gas explosion research in the United States. It also has developed unique instrumentation for testing the ignitibility and explosibility of flammable dusts and gases. In cooperation with representatives of the oil shale mining industry, the USBM has identified possible fire and explosion hazards that would have a direct impact on final mine designs and safety regulations and at the same time fulfill the operational requirements for efficiency while maintaining a high level of safety. This work is especially important since the proposed regulations for removing personnel to the surface prior to blasting in gassy non-coal mines are flexible enough to allow for some innovative changes in underground blasting procedures and adopting safer blasting agents. However, these proposed regulations could harden around the blasting procedures now practiced if this new information and research on alternative methods is not available.

Working together with several explosive manufacturers, the USBM has been testing various explosive formulations, including water gel and emulsion products, in the Lake Lynn Cannon Gallery (LLCG) to evaluate their relative incendivity compared to standard ANFO and other explosives. This report discusses the LLCG test procedures and summarizes the relative incendivity data obtained from the various explosives. Unfortunately, the continuation of the full-scale validation blasting in oil shale mines was not possible due to the closing of these facilities. However, the results on the full-scale field testing with these lower incendive explosive products in operating base metal mines will be presented. The development of instrumentation to monitor explosive incendivity characteristics such as detonation velocity and temperature will be presented.

OBJECTIVES

The USBM research program is focused on developing procedures and guidelines for acceptable underground blasting that fulfill the operational requirements for efficiency while maintaining a high level of safety when operating under gassy non-coal mine conditions. This work is aimed at providing new information, alternate methods, and innovation in underground blasting procedures. The results from this research will have direct impact on regulatory standards for blasting under gassy mine conditions. The Mine Safety and Health Administration (MSHA) is awaiting the results of this research to finalize and promulgate blasting regulations for Category 1-A oil

shale mines (Regulation 30 CFR 57.22601 was stayed pending the results of this research program). Many of the research findings on low incendive explosive products have direct applications to other non-coal mining industries.

EXPERIMENTAL PROCEDURE

LAKE LYNN CANNON GALLERY

Tests are conducted in the LLCG to evaluate the incendivity characteristics of stemmed and/or unstemmed explosives detonating into flammable methane-air atmospheres or fine coal dust clouds.

The LLCG is a 6.7-m long by 2.4-m diameter horizontal steel cylinder open at both ends (figure 1). A 1.5-m long by 0.6-m diameter steel cannon with a 57-mm diameter by 1.2-m long bore is mounted inside the gallery near one end. (pentaerythritol tetranitrate) The combustion products from a detonating explosive charge exit the cannon towards the geometric center of the gallery into a 10 pct methane-air or predispersed flammable dust atmospheres. These tests are to be used as one of many relative indicators of the explosive's true incendivity characteristics.

The explosives were received from the manufacturer in a prepackaged or bulk form. All of the explosives were tested in approximately 50-mm diameter packages and were loaded and tamped firmly to the back of the steel cannon. With the prepackaged explosives, the manufacturer delivered the product already packaged to the 50-mm diameter. The bulk repumpable products were generally delivered in 11 kg units which, prior to loading into the cannon, were repackaged in 50-mm diameter polyethylene lay-flat tubing. All of the cap-sensitive charges were initiated with a No. 8 copper detonator. In addition to the detonator, a 10 g PETN-based (pentaerythritol tetranitrate) booster unit was used with the blasting agents. An incision was made along the length of the stemming package containing the inert gelled water material. The stemming chub was then loaded into the cannon bore and tamped firmly against the charge which resulted in an effective coupling of the stemming and explosive to the cannon bore.

One of the LLCG tests determined the amount of stemming required to prevent the hot combustion products from a detonating charge from igniting a flammable atmosphere of methane gas. For this incendivity test with methane gas, a fixed-weight 500 g explosive charge was loaded to the back of the steel cannon. Various inert gelled water stemming amounts, in 50 g increments, were then tamped against the charge. The methane gas was injected into the gallery and was contained between plastic diaphragms secured at both ends of the gallery. A small permissible (explosion-proof motor) fan located inside the gallery mixed the methane gas with the air to provide a uniform flammable concentration. The methane concentration was continuously sampled through a small tube extending from the gallery to an infrared gas analyzer. The tests were made at a concentration of about 10 pct methane-in-air.

For the dust incendivity tests, a 5.0-m long steel V-trough was positioned on the gallery floor in front of the cannon. Detonating cord was attached to the bottom of the V-trough, and pulverized dust was loaded on top of the cord. When the detonating cord was set off, the dust was dispersed. The unstemmed charge in the cannon was initiated after a 500 ms delay to allow sufficient time for uniform dust dispersion throughout the gallery. The objective of

this test was to determine the minimum amount of unstemmed charge that would ignite the dust cloud. Figure 2 shows a typical dust ignition in the LLCG.

CRAWSHAW-JONES APPARATUS

To help understand this potential ignition source of excess fuel burning outside the cannon, tests were conducted in the Crawshaw-Jones apparatus (12). The Crawshaw-Jones is used for determining explosive gas production. This test was performed by detonating 300 g of a given explosive in a steel cannon and collecting the expansion products in a 90-L evacuated chamber (figure 3). The gases were analyzed by standard gas chromatography.

Table 1 lists the hydrodynamic-thermodynamic equilibrium calculations for several of the ANFO formulations tested. These calculations were provided by the explosive manufacturer. A brief definition (13) follows on the various calculated parameters listed in these tables; i.e., expansion work (E_{wk}), velocity of detonation (VOD), and Chapman-Jouquet (C-J) pressure. " E_{wk} is one of the most realistic measures of explosive power as it approximates the amount of work the gaseous products of the explosion can accomplish as they expand from the initial detonation conditions to atmospheric conditions. The VOD is the speed of which a detonation wave travels through a column of an explosive. The C-J pressure is the calculated pressure behind the rear boundary, or C-J plane, of the detonation front."

Table 1
Ideal detonation properties for various ANFO formulations

	AN-96 FO- 4	AN-95 FO- 5	AN-94 FO- 6	AN-92 FO- 8
Oxygen balance (pct)	+5.4	+1.8	-1.8	-9.1
Density (g/cc)	0.85	0.85	0.85	0.85
Ewk (cal/g)	985	875	906	850
Reaction Temp. (K)	2820	3060	3140	2990
VOD (m/sec)	4420	4620	4760	4770
C-J Pressure (kbar)	42	46	48	49
Gas (moles/100g)	4.34	4.33	4.38	4.57
Hydrogen (moles/100g)	<0.001	<0.001	0.075	0.363
CO (moles/100g)	<0.001	<0.001	0.033	0.175

Based on the Crawshaw-Jones and LLCG data, two factors to consider when formulating low incendive explosives appear to be oxygen balance and detonation reaction temperature. In the negative oxygen-balance cases (excess fuel), there is not enough oxygen to convert all of the carbon to carbon dioxide (CO_2). Therefore, carbon monoxide (CO) and hydrogen (H_2) are formed. More excess hot H_2 and CO are discharged from the borehole the higher the negative balance. It is believed that this excess hot fuels mixes with the air as it expands from the borehole, and burns. Experimentally, lean flammability limit for H_2 at 25°C is 4 pct for upward propagation, 6 pct for horizontal, and 8 pct for downward propagation (14-15). Using the Burgess-Wheeler law (16) to extrapolate to higher temperatures, the limits for upward propagation would be 1.9 pct at 500°C and 0.8 pct at 750°C. The ideal

detonation properties calculated for AN/FO ratios of 96/4, 95/5, 94/6, 92/8 and densities of 0.85 g/cc are given in Table 3. When the amount of FO falls below 5.6 pct, the reaction was oxygen-positive and nitric oxides were produced. In contrast, negative oxygen balances (excess fuel) tended to give H_2 and CO (17).

EXPERIMENTAL RESULTS

LAKE LYNN CANNON GALLERY RESULTS

Incendivity Tests With Flammable Gas:

Incendivity tests were conducted at the LLCG to determine preferred explosives that will reduce the probability of dust and/or gas ignitions during blasting operations under gassy mine conditions. Experiments in the LLCG have shown that a 500 g charge of standard ANFO (6 pct FO) detonated unstemmed from the steel cannon readily ignited flammable concentrations of CH_4 gas and/or fine oil shale dust. To reduce this incendivity level, tests have been conducted with various ANFO formulations. A 500 g charge of standard ANFO required 350 g of a tamped, inert gelled water stemming material (Table 2) to prevent the hot combustion products from igniting the surrounding gas mixture. [Note that gelled water stemming was determined from previous LLCG tests to be a more effective stemming material than stone dust, monoammonium phosphate (ABC) powder, or plain water packs.] When the fuel oil content of the ANFO was increased to 8 pct, an increased amount of gelled water stemming (400 g total) was required to prevent the gas ignition. When the fuel oil content was decreased to 4 pct, only 250 g of tamped gelled water stemming was necessary to prevent the methane ignition.

Because of the possibility that prilled ANFO (prill diameter range from 1100-1600 microns) was less able to sustain a steady detonation in the 2.25 in diameter cannon bore as compared to larger diameter holes and thereby might be contributing to the incendivity through partial deflagration, tests were conducted with a more dense ANFO (ground ammonium nitrate prills, minus 840 microns) in an attempt to approach more ideal detonation conditions. The LLCG results showed about the same level of incendivity with either whole prill or ground prill for both 5 and 6 pct fuel oil formulations.

Incendivity tests are ongoing at the LLCG with new and reformulated emulsion-ANFO blasting agents as received from various explosive manufacturers. Many of these pumpable blends consisted of 80 pct emulsion and 20 pct ANFO. Oxygen balancing a formulation can significantly reduce its incendivity. Comparing the oxygen balance percentages for the emulsion blend A (-9.5 pct) and the emulsion blend G (-1.8 pct), an increased amount of gelled water inert stemming was required with the emulsion blend A (Table 2) to prevent the methane-air ignition in the LLCG as compared to the nearly oxygen balanced blend G.

Substitution of materials in the formulation also reduced the explosive's incendivity. The blends which contained ammonium nitrate (AN; blends A and G) in the base emulsion were more incensive (Table 2) than those which contained calcium nitrate (CN; blends H and I) or sodium nitrate (SN; blends B, C, and D); and, thereby, required more inert stemming to prevent ignition of the methane zone under the LLCG test conditions. A 500 g charge of these lower incensive blends required only 100-150 g of tamped gelled water stemming to

Table 2

Minimum gelled water inert stemming weights
to prevent 10 pct methane-air ignitions
at the LLCG.

Product	stemming weight (g)	
	IGNITION	NON-IGNITION
Emulsion Blend A ¹	400	450
Emulsion Blend C	100	150
Emulsion Blend D	50	100
Emulsion Blend G	250	350
Emulsion Blend H	100	150
Emulsion Blend I	100	150
ANFO 96/4	200	250
ANFO 95/5	300	350
ANFO 94/6 ²	300	350
ANFO 92/8	350	400
Dynamite A ³	100	150
Water Gel A ⁴	250	300
Water Gel B ⁵	250	300
Emulsion A ⁶	250	300
Emulsion B ⁷	200	250
Emulsion C ⁷	400	450
Emulsion D ⁷	400	450

¹All of the emulsion blends are 80 pct emulsion and 20 pct ANFO.

²Standard formulation of ammonium nitrate - fuel oil, 6 pct fuel oil.

³Semigelatin dynamite; type typically used in base metal mines.

⁴Cap-sensitive water gel.

⁵Water gel blasting agent.

⁶Emulsion blasting agent.

⁷Cap-sensitive emulsion.

Note: The explosive charge for each test was 500 g.

prevent the ignition of a 10 pct methane-in-air zone compared to 350 g for the standard ANFO. The lower incandive blends, as determined from the LLCG tests, were essentially oxygen-balanced and substituted AN with either SN or CN in the emulsion portion of the blend. In the LLCG tests, the emulsion-ANFO blends were generally the least incandive blasting agents tested since they required the least amount of stemming to prevent ignition of the methane. Emulsion blend D exhibited the lowest incandivity characteristics of any of the blends and was field tested in several oil shale mines (18).

Two water gel based explosives were also tested in the LLCG. Table 2 lists the amount of inert gelled water stemming material required to be tamped in front of the explosive charge in the cannon bore so as to prevent ignition of the methane gas in the LLCG. Water gel explosives A and B required 300 g of the inert stemming to prevent the gas ignition compared to 100 to 150 g for the emulsion-ANFO blends C, D, H, and I. Standard ANFO required 350 g of the

gelled water material to prevent the gas ignition. The reaction temperatures, as determined from hydrodynamic-thermodynamic equilibrium calculations provided by the explosive manufacturers, were 2,000 to 2,680 K for the emulsion blends and 2,675 K for the water gel explosives; these temperatures are significantly lower than the 3,140 K for standard ANFO. Interestingly, the water gels showed only marginal improvement relative to standard ANFO in preventing the gas ignitions; whereas, the stemming requirements to prevent the gas ignition with the emulsion blends were much lower than that for ANFO. One explanation is that the water gel products contained dissolved ammonium nitrate, whereas the emulsion blends replaced the more incensive AN in the 80 pct base emulsion with much less incensive CN or SN. Incendivity data from the LLCG has shown that the explosive products which contained AN ignited the methane gas more readily than those which consisted of other less incensive materials. The water gels were formulated to have a low detonation temperature and to produce a minimum of hot particles after detonation. These water gel products contained very little aluminum, which not only is a source of hot particles, but can also produce hydrogen gas as a detonation product.

Incendivity tests on several IRECO explosive products were conducted in the LLCG. A repumpable, bulk emulsion A required 300 g of a tamped gelled water inert stemming material to prevent the detonation of 500 g charges of the emulsion A from ignited a flammable methane-air atmosphere. The cap sensitive emulsions C required 250 g of the tamped gelled water to prevent the methane ignition. These results were compared with the 350 g of tamped gelled water stemming that was needed to prevent the gas ignition when detonating 500 g charges of ANFO, 150 g of stemming for the emulsion blend D, and 300 g of stemming each with cap-sensitive water gel A and B.

Incendivity tests were then conducted in the LLCG on two additional cap-sensitive emulsion C and D products manufactured by ICI, Canada. These products were being considered as replacements for the higher incensive ANFO and dynamite products which have caused sulfide dust ignitions during blasting operations in base metal mines in Alaska and Canada. These products also have direct application to blasting operations in gassy oil shale mines. Data from the LLCG tests have shown that the two products were slightly more incensive than ANFO when detonating 500 g stemmed charges into a flammable methane-air atmosphere. To prevent the gas ignition, 450 g of gelled water inert stemming was required to be tamped against either of the ICI emulsions; whereas, 350 g of the stemming was required with the ANFO charges.

Using the 57-mm diameter bore steel cannon loaded with the emulsion blend D blasting agent, tests were conducted to determine the minimum amount of a tamped gelled water inert material necessary to prevent the gas ignition regardless of charge mass. Initial tests have shown that a 500 g charge of the emulsion blend D required 150 g of gelled water stemming to prevent the gas ignition. A maximum cannon charge weight of 2000 g of the emulsion blend D required 500 g of stemming. Additional tests are scheduled to find the optimal amount of stemming which will prevent the gas ignition with any size charge in the steel cannon. Results from these studies will be instrumental in recommending safe stemming requirements for the non-coal mining industry when blasting in hazardous conditions.

Incendivity Tests With Combustible Dust:

Table 3 lists the maximum unstemmed charge weight for nonignition and the minimum unstemmed charge weight for ignition of a flammable, predispersed concentration (200 mg/L) of coal dust in the LLCG. A standard Pittsburgh seam pulverized coal dust was used during these tests due to its low flammability limit, the ease to which it dispersed, and its availability. This pulverized coal dust has been used for many years as a comparison standard for flammability. The coal dust was even more hazardous than the oil shale or sulphide ore dust in that it is more easily ignited and required less dust to form a flammable concentration. Therefore, the LLCG incendivity results were conservative. However, data from the Bureau's Bruceton Experimental Mine has shown that the relative incendivity ranking of various explosive products which were tested against predispersed coal dust maintained their incendivity ranking when detonated into predispersed oil shale dust clouds of varying grade or assay (11). When detonating unstemmed charges from the steel cannon in the LLCG, all of the hot combustion products were ejected out of the bore and into the gas or dust atmosphere. When detonating in ore, much of the hot combustion products are more rapidly cooled due to the shot hole expansion during the fragmentation process.

Table 3

Relative incendivity of unstemmed explosives
in a flammable coal dust cloud at the LLCG

Product	Minimum charge (g) for ignition	Maximum charge (g) for nonignition
ANFO 94/6 ¹	100	--
Emulsion Blend D ²	2000	1750
Water Gel A & B	--	2000
Dynamite A	300	250
Dynamite B ³	600	500
Emulsion A	800	750
Emulsion B	500	400
Emulsion C	2000	1750
Emulsion D	1250	1000

¹Standard ammonium nitrate - fuel oil, 6 pct fuel oil.

²80 pct emulsion and 20 pct ANFO blasting agent (sodium nitrate in base emulsion).

³Permissible granular dynamite.

Note: Maximum cannon charge weight is 2000 g.

Standard ANFO initiated unstemmed from the 57-mm diameter cannon bore readily ignited the coal dust cloud in charge weights as low as 100 g. It required 2,000 g charges of the unstemmed emulsion blend D to ignite the coal dust; 1,750 g charges did not ignite the dust. With the water gel explosive A or B, maximum cannon charge weights of 2,000 g did not ignite the dust cloud with either explosive. Unstemmed 800 g charges of the emulsion A ignited the dust; 750 g charges did not. [It is not clear at this time why the water gel

products exhibited lower incendivity characteristics relative to the coal dust than that to the methane gas. Additional research is planned in this area.] Emulsion blend D exhibited the lowest incendivity characteristics, particularly when detonated into a flammable methane-air atmosphere, of any of the blends and showed promising results during full-scale field testing in several oil shale mines in western United States (10,18). The water gel A and the emulsion A products have also significantly reduced the dust ignition hazards associated with blasting operations in high sulphur-bearing ores in base metal mines in the United States and Canada.

Incendivity testing against predispersed coal dust in the LLCG was also completed on IRECO's cap-sensitive emulsion C. Tests have shown that the detonation of 400 g unstemmed charges of this emulsion C product did not ignite the dust cloud; whereas, the detonation of 500 g unstemmed charges did. An emulsion A blasting agent was also tested against an explosible concentration of predispersed pulverized coal dust. Unstemmed 750 g charges of the emulsion A did not ignite the dust; 850 g unstemmed charges did ignite the coal dust cloud.

This explosive incendivity research has direct application to other non-coal mining industries, such as sulfide ore, in reducing the probability of gas and/or dust ignitions following blasting operations. The use of ANFO during blasting operations in oil shale has resulted in methane gas ignitions and fires and has caused dust ignitions in sulfide ore mines. A cap-sensitive semigelatin dynamite A (IRECO's Iresplit D) which had also been used during blasting operations that resulted in dust ignitions in sulfide ore mines was tested for its relative incendivity characteristics in the LLCG. Unstemmed charges 300 g of dynamite A ignited the predispersed coal dust cloud; unstemmed 250 g charges did not.

Two other explosive products, emulsion C and D, were then tested as possible replacement explosives to the highly incendive ANFO and dynamites when conducting blasting operations in areas with combustible dusts. Against an explosible predispersed coal dust concentration, the detonation of 1,750 g unstemmed charges of the emulsion C did not ignite the dust; 2,000 g unstemmed charges did ignite the dust. With the emulsion D product, 1,000 g unstemmed charges did not ignite the dust and 1,250 g unstemmed charges did ignite the coal dust cloud. These LLCG results show that both of these emulsion products are significantly less incendive than ANFO when tested against explosible concentrations of predispersed coal dust.

This data is being compared with other explosive products tested in the LLCG and is used to evaluate the relative incendivities of the explosives. The Cannon Gallery tests serve as one method in selecting explosive products which may have less of a probability to cause a gas and/or dust ignition following underground blasting operations. To date, the water gel products, the emulsion blend D, and the emulsion products showed desirable lower incendive characteristics when compared to ANFO and several dynamite products when initiated unstemmed into an explosible concentration of pulverized coal dust in the LLCG.

Luminosity Test Results:

Tests were also conducted in the LLCG to evaluate the explosives' luminosity since the extent of flame outside the cannon is presumably related to the incendivity (10). For those tests, 500 g charges of various stemmed and unstemmed explosives were loaded into the cannon and detonated, thereby

allowing the combustion products to discharge into the gallery. An optical flame sensor was mounted inside the gallery to measure, in terms of duration and intensity, the flame exiting the cannon bore. With standard ANFO, the detonation of an unstemmed charge produced highly luminous by-products which were observed for over 15 ms. The unstemmed water gel A and emulsion blend D explosives produced detonation products which were visible for 12 ms but with a 50 pct lower relative luminosity compared to a similar charge of ANFO. The explosives were then stemmed with 150 g of a tamped inert gelled water material to evaluate the effect of the stemming on the detonation by-product luminosity. The gelled water stemming effectively contained the detonation products within the bore for a longer period which resulted in a lowering of the temperatures of these products prior to exiting the bore. The detonation of the stemmed ANFO charge still resulted in 15 ms of luminosity; however, the intensity was at a reduced level. The stemmed water gel A and emulsion blend D charges showed no evidence of any luminosity from the detonation by-products exiting the cannon bore. The USBM is currently developing a temperature sensor designed to more accurately measure these bore hole exit temperatures (see Sensor Development section).

New Stemming Device:

In addition to evaluating blasting agents and explosives, stemming methods were also being evaluated as a means to reduce the gas and/or dust ignition hazard associated with blasting operations. One method used the gelled water inert as a stemming material. The gelled water had been shown in both LLCG and full-scale mine tests to be quite reliable and durable. However, the commercially available gelled water inert is relatively expensive with high shipping costs. An alternative stemming method is to use plastic plugs which are placed in the bore holes then inflated with water.

Tests were conducted in the LLCG to evaluate a newly developed water plug device for use as a stemming agent. This device was manufactured with 16-mm thick polyethelyene and was designed to be inflated with water within the borehole. The method for the water inflation consisted of inserting a hollow needle within a specially designed valve on one end of the water plug, inserting the unit into the borehole, water filling to 0.14 kPa (20-psi), then removing the needle from the filled plug. The result was that the filled water plug was coupled tightly against the charge and along the bore hole surfaces. The LLCG tests were conducted to compare the performance of the water plug to that of a gelled water material in preventing the ignition of a flammable methane-air zone from the detonation of a 500 g charge of ANFO. To prevent the methane ignition, 350 g of a tamped gelled water stemming material was needed. A custom-sized water plug properly filled with 350 g of water also successfully prevented the gas ignition.

To determine to what extent borehole coupling improved stemming efficiency, several shorter length plugs were tested against the methane atmosphere. The plugs, with lengths ranging from 10- to 14-cm, held less water (130- to 240-g). Unfortunately, the manufacturer provided the wrong diameter plug for the LLCG's cannon bore. Tests were conducted with the smaller diameter plugs inflated to 0.21 kPa (30-psi). This additional inflation pressure provided the necessary coupling to the cannon bore without bursting the plugs. The plug was positioned in the cannon bore against the 500-g charge of ANFO and then inflated with water until the plug had reached the desired internal pressure. A plug 11.4-cm long by 5-cm-diameter contained

165 g of water and successfully prevented the hot products from the detonating ANFO charge from igniting the flammable methane-air atmosphere. A 10-cm long plug (130 g of water) did not prevent the methane ignition.

These water plugs provided a greater degree of protection against the methane ignitions as compared to the previously most effective gelled water stemming material. The enhanced coupling to the cannon bore effectively contained, for a longer period of time, the hot detonation products within the cannon bore. The result was that these products exited the bore at lower temperatures and thereby required less stemming to prevent the methane ignition. The cannon provided for a worst case scenario since all of the detonation gases exited the bore; whereas under actual mining conditions, much of the hot detonation products/gases would be vented and cooled into the broken rock. These plugs can also be manufactured so that they contain dry guar gum powder and salt which after filling with water (after placement in the hole) would result in a gellatin consistency that would be more resistant to leakages. A cost benefit could also be achieved in that there would be very little cost associated with the shipping of the empty plugs to the mine sites as compared to the pre-packaged stemming materials.

CRAWSHAW-JONES APPARATUS TEST RESULTS

Preliminary small-scale laboratory tests have been conducted to collect the gases produced from detonating explosives. Analyses has shown that the more incendive explosives generally generated larger quantities of flammable gases (hydrogen and carbon monoxide) than do the low incendive explosives. Hydrogen and atmospheric air could form a flammable mixture. If this mixture was ignited by the hot particles generated by the detonation of the longer delay holes in the blast round, the resultant heat and flame could ignite the dust and/or gas cloud.

Table 4 shows the gas analyses from the Crawshaw-Jones tests for various ANFO formulations. Relative agreement with the calculations in Table 1 was noted in that the predicted H_2 and CO concentrations increased with increasing FO. Also shown are comparable Crawshaw-Jones data for emulsion-ANFO blends. In all but one of the emulsion blends tested, results showed that the blends generally produced less H_2 and CO than standard ANFO (94/6). The one that did produce more H_2 and CO than ANFO was the emulsion blend (A) containing AN, instead of CN or SN, in the base emulsion; and, it had a high negative oxygen balance (-9.5). Generally, the more oxygen balanced blends produced less H_2 and CO than the negative oxygen blends when comparing similar formulations (B and D blends versus C blend; H blend versus I blend). Likewise, the blends which contained AN in the base emulsion generally produced more fuel than the blends which contained SN or CN in the base emulsion when all other factors remained relatively constant (compare blend A with blends C and I; blend G with blends B, D, and H). Once again, relative good agreement between the Crawshaw-Jones data and the equilibrium calculations were obtained with the emulsion blends.

Tests have also been completed in the Crawshaw-Jones apparatus to measure the gaseous detonation products of several additional explosives that were tested in the LLCG. These explosives included an emulsion A blasting agent, a cap-sensitive emulsion B, and a semigelatin dynamite A. Laboratory analyses of the gases showed that the dynamite A and emulsion B products generated

Crawshaw-Jones data for various explosive products

	Moles/100g		
	H ₂	CO	NOX
ANFO 96/4	0.013	0.023	0.047
ANFO 95/5	0.081	0.062	0.031
ANFO 94/6	0.145	0.109	0.014
Blend (A)	0.181	0.105	0.002
Blend (B)	0.015	0.044	0.164
Blend (D)	0.009	0.020	0.072
Blend (G)	0.067	0.054	0.007
Blend (H)	0.036	0.038	0.060
Blend (I)	0.080	0.070	0.026
Water gel A	0.078	0.041	0.004
Water gel B	0.114	0.066	0.006
Dynamite A	0.336	0.315	0.001
Dynamite B	0.153	0.154	0.004
Emulsion A	0.078	0.015	0.002
Emulsion B	0.140	0.074	0.001

significant amounts of hydrogen gas as compared to the explosive products (water gel A and emulsion-ANFO blend D) which were determined to be less incendive relative to the LLCG tests (see table 2). As additional explosive product detonation gases are collected and analyzed, comparisons between low and high incendive products (based on LLCG tests) will continue to be made as another method to aid in the understanding of an explosive's incendivity.

To help visualize the effect of the H₂ and CO on the ignition process, high speed photographs were taken of these hot detonation products exiting from the steel cannon. Results indicated that the time duration of the flame outside the cannon increased with increasing FO. Values ranged from 5 to 10 ms with the near oxygen balanced emulsions to 30 to 40 ms for the fuel rich formulations. It is believed that this longer lasting envelop of flame was contributing to the incendivity of these formulations. This flame envelope may be associated with the hot combustible fuels, particularly due to the high diffusivity of H₂, which mixes with atmospheric oxygen and burns outside the borehole. Additional research is needed in this area.

FULL-SCALE FIELD STUDIES

BLASTING VALIDATION RESULTS

An explosive, when designed to be low incendive to deter dust ignitions, may give up some of its formula strength to result in a product with a lower detonation temperature and little or no hot particles. This must be a major concern for manufacturers and mine operators. The LLCG tests are an experimental method for determining the relative incendivity of explosives and do not assess the fragmentation characteristics of the explosives. Full-scale field validation tests are one reliable method for evaluating the performance of any explosive. Several experimentally determined low incendive explosive products have been identified through data gathered from the LLCG tests. A low incendive emulsion-ANFO blend D was previously tested, with much success,

at three oil shale mines in the western U. S. (10,18). Due to the closing of the oil shale facilities shortly after the commencement of this program, no full-scale validation tests in oil shale could be conducted. However, there is a direct benefit to other noncoal mining operations. Full-scale production blasting in base metal mines in Alaska and Canada were conducted using two of the experimentally determined low incendive products (19). These mines were experiencing dust ignitions following blasting in areas with high sulphur-bearing ore.

Kennecott Greens Creek Mining Company, working in conjunction with an explosive manufacturer and the USBM, has conducted an extensive testing program with a lower incendive water gel A (ETI's NBL 499) and a pumpable emulsion A (IRECO's Iregul RU) at its Greens Creek Mine, located on Admiralty Island 29 km southwest of Juneau, Alaska.

The ore types that comprised the mineralized horizon at the Greens Creek Mine were basically divided into two types; a massive sulphide ore that can be composed of 80 to 90 pct pyrite with a low base metal content or a massive sulphide ore formed with a high base metal content and a low pyrite (10 to 15 pct) content. Historically, the fine grained - high sulphide units have created the greatest difficulty in controlling sulphide dust ignitions. A typical production drift was 3.7 by 3.7 m. Blasting was conducted using non-electric detonators, high velocity detonation cord, and a fuse/detonator initiation system. The cross-sectional area of the drift ranged from 9 to 28 m². The holes in the pattern were drilled to a depth which ranged from 2.4- to 3-m.

The first sulphide dust ignition at the Greens Creek Mine occurred in 1989. Up until the introduction of the lower incendive explosives, dust ignitions have occurred infrequently but at the same time had continued. No major damage had been sustained but production losses averaged about \$40K (U.S.) per incident; primarily due to loss of production while checking the mine for sulphur dioxide. Minor injuries to employees have occurred and were associated with the inhalation of combustion products.

When the Greens Creek Mine first began to experience problems with sulphide dust ignitions, their management instituted strong preventative measures which included: thoroughly washing down of the face and the ribs and back within 30 m of the face; stemming all loaded holes with water-filled bags; and utilizing a water/air mist spray before and during blasting. These procedures were labor intensive and, while reducing the number of incidents, did not eliminate them. In fact, the use of water caused other problems. The country rock at the mine is a complex package of strongly altered volcanic rock which breaks down quickly when exposed to water. The preventative measures designed to limit the sulphide dust ignitions seriously degraded haulage roads, and production was adversely affected.

Testing of the low incendive water gel A product was conducted during full-scale production blasting. Initially, the testing was limited to the high sulphur-bearing areas in the mine that were prone to dust ignitions. The standard preventative measures already in use were employed with these first blasting rounds. Nearly 4,750 kg (equal to approximately 32 average rounds) of the water gel A were consumed using the full precautions. No sulphide dust ignitions had occurred. As testing progressed, the control procedures were gradually stepped down. The water/air mist spray was first eliminated while maintaining the washing down of the drift and the use of water stemming.

After successfully using an additional 8,430 kg (equal to approximately 56 average rounds) of the water gel A with no dust ignitions, the use of water stemming was then dropped. Since that time, Greens Creek has not experienced any sulphide dust ignitions when using the water gel A.

The blasting efficiency of the water gel A at Greens Creek had been very high. The 38-mm diameter by 400-mm long water gel cartridges tamped well and compaction ratios of 90 pct or better were the norm. This high degree of coupling improved the brisance and work effective characteristics of the explosive. The powder factor ranged from 3 to 3.8 kg/m³ (5.1 to 6.4 lb/yd³) and averaged 3.6 kg/m³ (6 lb/yd³). The holes were initiated with long period non-electric detonators.

Greens Creek experienced three sulphide dust ignitions in a two week period when blasting with their usual gelatin dynamite product. A temporary gap in the supply of the low incendive water gel A had created the need to return to the full sulphide dust ignition precautions while using the semigelatin dynamite. Past experience had shown that extreme caution was warranted when blasting in the stope where these ignitions were occurring. Two days following the last ignition when using the dynamite products, the supply of the water gel A was re-established. The first round detonated in this stope using the water gel A used full precautions. No sulphide dust ignition occurred and the precautions were reduced to only washing down of the blast area and beyond. This also resulted in no dust ignitions. The Greens Creek personnel had developed confidence in the water gel A and undertook a project to test the product under extreme conditions. A stope had been mined to a point where a slash while retreating method was being employed. During the occurrence of the dust ignitions while using the gelatin dynamite, only one slash, no greater than 3.7 m high by 3.1 m long by 3.1 m deep was taken. This procedure was in effect to minimize dust generation and, hopefully, to eliminate dust ignitions. During the experiment to evaluate the ability of the water gel A to eliminate ignitions, slashes on each side of the initial drive were detonated at the same time with substantial delay. Four such experimental blasts were conducted with this configuration and no sulphide dust ignitions occurred. Again, the only precautions taken was washing down of the blast area and beyond. All slash sizes were approximately 3.7 m by 3.1 m by 1.8 m. After over two years of full production use, no sulphide dust ignitions have occurred at the Greens Creek Mine when using the water gel A product.

Greens Creek has since switched to a pumpable emulsion product (emulsion A, see table 2). No sulphide dust ignitions have occurred when using this bulk product (over 800,000 kg of emulsion A). At Greens Creek, the overall blasting costs were significantly reduced when using this bulk product. Pumping reduced the labor involved in the loading process by at least half compared to loading times with the pre-packaged products. Pre-blast precautions had been even further reduced to only occasionally washing down the drift to remove fine sulphide dust deposits. Another benefit attributed to these low incendive explosives was improved haulage roads since the use of water to control the sulphide dust ignitions had been nearly eliminated.

Initial blasting with the water gel A and emulsion A were conducted in 41-mm diameter holes and resulted in no sulphide dust ignitions. To optimize explosive performance and rock fragmentation, 44-mm diameter holes were being used with much success with both the pre-packaged and bulk products. No sulphide dust ignitions have occurred when using the low incendive products in the 44-mm diameter holes.

The lower incendive water gel explosives have also been used with success in two Canadian sulphide ore mines to reduce the probability of sulphide dust ignitions following blasting operations; at the Westmin Resources Limited H-W Mine on Vancouver Island, British Columbia and at the Hudson Bay Mining and Smelting Company Limited Ruttan Operation located near Leaf Rapids, Manitoba. The Ruttan Operation was averaging 2.7 sulphide dust ignitions per month. The sulphide dust ignitions accounted for 14 pct of their blast delays and these delays averaged 2.6 h per occurrence. They considered that any blast which had produced sulphur dioxide to be a sulphide dust ignition. Mine re-entry following blasting operations was restricted until the ventilation system had removed and/or diluted the toxic gases to a safe level. Their policy was to send the crew home if these toxic gases were not cleared within 4 h which often resulted in lost production time. This occurred 1-2 times per month. No sulphide dust ignitions had occurred when using the low incendive water gel in place of ANFO during full-scale blasting operations at these two mines.

METHANE EMISSIONS IN OIL SHALE

As part of a continuing long term study in gas emissions from oil shale mines, gas samples were collected to measure the background methane emissions from the Horse Draw oil shale mine in Colorado and the White River Shale Project in Utah.

Samples were taken through the vent pipe at the sealed shaft of the Horse Draw mine in Colorado. All mining at Horse Draw ended in late 1981. The Horse Draw mine is located deep in an oil shale formation in the Piceance Creek Basin below two aquifers and at least 24 km away from the nearest outcrops. Analyses of the samples has shown that the mine was liberating methane at a rate of 0.62 m³/min. This was only slightly lower than the rate of 0.74 m³/min that was measured in 1988 (9). The aquifers act as seals forcing the methane liberation through the shaft which intersects the gas horizon in the shale formation.

Gas samples were also collected from the fan house and at several locations underground at the idle White River Shale Project in Utah. Based on the measured natural ventilation rate, the background methane emissions had shown that the mine was liberating methane at a rate ranging from 0.02 to 0.05 m³/min. The methane emissions at White River continued to decrease. At the mine's closing in 1986, the analyses of gas samples had shown that the mine was liberating methane at a rate of approximately 0.3 m³/min; analyses of gas samples in 1988 had shown a rate of 0.04 to 0.08 m³/min (9). This reduction in the methane emissions from the developed entries will be instrumental in developing ventilation requirements for similar operations in the future.

The majority of the methane emissions in oil shale mines was found to occur during the blasting, mucking, and grinding operations. Oil shale does not liberate methane gas nearly as readily as coal due to its much lower permeability.

SENSOR DEVELOPMENT

FIBER OPTIC RATE PROBE

Tests are continuing in the LLCG to evaluate the performance of the explosives in the Cannon Gallery. One of the test series in the LLCG was designed to measure the velocity of detonation of explosive products initiated in the steel cannon. Detonation velocity is an important criteria for determining an explosives' performance. Prior to standardizing testing of blasting agents in the Cannon Gallery, the tests with the rate probe will verify that these blasting agents are indeed detonating at ideal velocities in the 5.7-cm-diameter bore.

Initially, attempts were made to measure the detonation velocities of the explosive charges using coaxial cable reflectometry and resistance wire probes. Data from these tests showed that these probes were very accurate in calculating the detonation velocity of unconfined cap-sensitive detonating cord and other unconfined cap-sensitive high explosives. However, a 0.9-m charge of ANFO detonated within the cannon resulted in unreasonably high velocities. The detonation velocity measured during one test with the ANFO approached that of the speed of sound in steel. The sensitive probe wires may have been reacting to the shock wave propagating through the charge/cannon. This shock wave was generated by the initiation of the detonator/booster. During other test trials, it was speculated that the firing line, which was energized during the entire data gathering period, contributed to the erratic velocity data. To eliminate these factors, a 700 ms delay detonator attached to the booster charge was used to initiate the blasting agent. This detonator was initiated in a manner which allowed the firing line to be de-energized prior to the blasting agent detonation. The rate probe data from these tests still did not provide reproducible detonation velocity data for charges of ANFO or high explosive cap-sensitive charges.

To accurately measure the detonation velocities in the cannon, a fiber optic rate probe is being developed. This probe, based on a redesign of an existing USBM fiber optic probe (20), should more accurately measure the explosive detonation velocity in the cannon and/or a blasthole. The modified probe design will consist of twenty juxtaposed optic strands whose open ends are spaced at 5-cm intervals along the length of the explosive charge. A signal (pulse of light) will be generated as a function of time as the detonation front reaches each of the fiber strand locations. The detonation velocity can then be calculated based on these times and the spacings between the strands. This type of probe can be a practical alternative to the more complex and expensive coaxial cable reflectometry and resistance wire probes.

Tests were conducted using both a modified single fiber probe and a four fiber probe. An ionization device was placed juxtaposition to the fiber end to detect when the detonation reaches the end of the fiber buried in the explosive charge. The results showed that due to the optical transparency of the explosive, light from the detonation was detected by the fiber prior to the time the detonation front reached the fiber end. Methods to circumvent this problem were implemented. One method involved the coating of the ends of each strand to prevent light (produced from the detonation of the explosive) from entering prior to the time that the detonation front reached the end of each strand. In addition, the electronics were modified to incorporate a bank

of 10 megasecond counters to measure the time interval of the propagating detonation between fiber strand ends.

Various types of fiber (plastic or ribbon), which could provide a better signal, were also being explored. These compacted fiber ribbons would improve the packaging characteristics of the probe and optimize signal strength. One of the three types of fiber ribbon was tested and it was concluded that the traveling light strength through the core was not satisfactory. To acquire better results, the electronic circuits were placed on a printed circuit board (PCB). The electronics were modified to ameliorate the temporal resolution of the probe. Bench tests showed that the unit has a resolution of 0.5 usec. Once the rest of the probe is complete, this modified probe will then be tested in the LLCG.

The data collected with this probe will allow for the determination of proper charge length and detonator/booster size to ensure ideal detonation velocities in the cannon. Once it is determined that the non-cap sensitive explosive products are detonating at ideal velocities in the LLCG, the testing to evaluate the data from the LLCG to that from the Permissibility Gallery located in the Bruceton facility will resume. These comparisons will be evaluated based on the relative data from each facility as part of the research effort to standardize the LLCG testing of non-permissible explosives for use in non-coal mining applications.

TEMPERATURE SENSOR

Efforts are continuing on refining techniques for measurement of the temperature profile of the detonation products exiting the cannon bore. Exhaust temperature measurements are important in evaluating both the explosive's incendiarity characteristics and stemming performance in cooling the detonation products exiting the bore.

Tests were conducted with a commercially available infrared video recording system to evaluate its ability to measure the temperature profile of the hot combustion products exiting the cannon bore following the detonation of an explosive charge. The infrared camera was first calibrated at 50° C intervals from 200 to 600° C using a black body device. Without filters, the camera monitored temperatures to within 20° C of the actual black body temperature. Without a filtering device on the camera lens, the system was designed to measure temperatures up to 600 degrees C before saturation occurs; using the No. 1 filter, the camera should record temperatures to 1500 degrees C. The camera was not able to maintain accurate measurements the temperature within the black body when neutral density filters were attached to the lens. Neutral density filters should allow the camera to monitor temperatures above the 600° C maximum. The expected exhaust temperatures of the detonated explosive at the cannon bore are expected to be well above 1000° C.

Laboratory tests were then conducted to determine the capabilities of this infrared camera system for measuring temperatures associated with rapid ignitions and detonations. The infrared video system was used to view the flame from the 1.2-L furnace. The furnace temperature was set to 600 C, and the coal dust was burned to increase the emissivity. Seven tests were recorded on videotape and reviewed frame by frame. On the average, ten frames were collected for each test. The maximum temperatures ranged from 250-270 C. The actual temperatures were much higher. The transparency of the flames

(emissivity less than 1.0) was determined to be the reason for the low temperature measurements.

To create a test where the emissivity was closer to 1.0, an explosion was set up in the 20-L chamber. A gold mirror was placed at an angle above the sapphire window on the top of the chamber. The camera viewed the explosion in the mirror and recorded the tests on videotape. Since the reflectivity of the mirror was approximately 98 pct and the transmission of the sapphire window was 80 pct, the emissivity was set to 0.8. The explosions lasted approximately 0.5 s. Ten to 15 frames were collected and the maximum temperature appeared on 3-4 frames. The first few tests showed temperatures much less than expected. The concentration of coal dust was increased to increase the emissivity. The infrared camera could not accurately measure the peak temperatures during the rapid ignitions of methane and coal dust in the 20-L chamber. Similar results using the infrared camera were evident from attempts to measure the borehole exhaust temperatures of the hot combustion products of detonating explosives within a steel cannon.

A photometric sensor is being developed to more accurately measure these bore hole exit temperatures. The ordered components for the sensor have been delivered and the sensor is currently being built. Once completed, the temperature sensor will be tested in the LLCG to measure the borehole exhaust temperatures generated from the detonation of various explosive charges.

CONCLUSIONS

Tests conducted at the U.S. Bureau of Mines Lake Lynn Laboratory Cannon Gallery provide a means of evaluating the relative incendiary characteristics of an explosive product. Three explosives, an emulsion/ANFO blend, an emulsion product, and a packaged water gel were determined, through Cannon Gallery tests, to exhibit very low incendiary qualities as compared to ANFO and dynamites which are typically used in non-coal mining operations. Determinations continued in the cannon gallery on preferred stemming agents as another means to control blast-induced gas and/or dust ignitions. A water stemming plug was evaluated in the cannon gallery and shown to be a better stemming device, both in terms of effectiveness and overall cost, as compared to the previously most effective inert gelled water material. The lower incendiary products were then evaluated in operating mines.

Full-scale field testing of the experimental low incendiary explosives was conducted at sulphide ore mines in Alaska and Canada. The water gel and pumpable emulsion products have both been shown to be an effective, lower incendiary explosive in validation tests conducted at Kennecott Greens Creek Mining Sulphide Ore Mine. After several years of testing and full-production use, Greens Creek had not experienced any sulphide dust ignitions following blasting operations when using these lower incendiary explosive products.

Two instrument sensors are being designed and built to enhance the understanding of explosive incendiary. A modified fiber optic rate probe has been designed and built to more accurately measure the detonation velocities of explosives within the bore. A temperature sensor is currently being designed to accurately measure the detonation products exiting the bore hole.

Based on the positive laboratory and field testing results, these low incendiary explosives show promise as a means of greatly reducing the occurrence of dust and/or gas ignitions following blasting operations in noncoal mining applications.

RECOMMENDATIONS

Continued research is needed on the development of safer explosives and procedures for blasting in the presence of combustible dusts and methane gas in non-coal mines. Small-scale research in the Bureau's LLCG has been effective in determining the incendiarity of blasting agents and should be used to evaluate proposed new blasting agents. Also in the gallery, measurements can be gathered on the after-burning of various stemmed/unstemmed explosives. More data on the temperatures and extent of afterburning may lead to a better understanding of how best to prevent the ignition of flammable gas or dust atmospheres.

More full-scale validation tests in operating mines need to be conducted to evaluate low incendiary blasting agents and safer blasting procedures before formal recommendations are made. Most importantly for oil shale mines, these tests need to be conducted in the presence of methane to determine and confirm the safe amount of stemming material needed for each blast hole. Additional studies need to be conducted in non-coal mines to determine the minimum spacing required between holes to avoid shock-induced desensitization of the explosives in nearby holes.

A need also exists for optimizing drill patterns. Computer modelling may, to some extent, generate drill patterns to promote the desired fragmentation. In addition to optimizing the drill patterns, the automation of the jumbo drills would result in a more accurate blasthole placement while maintaining the recommended spacings between holes so as to minimize the desensitization of the blasting agent in adjacent holes.

The development of a nonelectric initiation system for use in gassy atmospheres would be of great benefit to the mining industry. The majority of blasting operations in nongassy mines rely on nonelectric methods for initiation of the explosives, mainly due to the immunity of nonelectric systems to stray electricity. This use of nonelectric initiation eliminates one of the major causes of unwanted premature detonations in blasting, thus improving safety. However, nonelectric initiation systems, as they exist now, cannot be used in flammable atmospheres due to the inherent potential for igniting that atmosphere. A nonelectric initiation system that would not present a hazard in gassy mines would greatly improve the safety of blasting operations. Any proposed, new nonelectric initiation systems would have to be evaluated for safe use in gassy mines.

There is also a need to develop a toxic fumes standard for approval of various low incendiary blasting agents. Reduction in the amounts of toxic fumes generated in the blasts would improve safety and increase efficiency and productivity by allowing work to commence sooner in the shot area. Several areas affecting toxic fumes should be examined. First, a standard test needs to be developed to determine the toxic fumes generated by blasting agents. Tests exist for cap sensitive explosives, but not for blasting agents. Second, the toxicity of blasting fumes should be better defined. Currently, guidelines exist that only limit the total quantity for as many as seven types of fumes. Since the toxicity of some of these types of fumes is greater than that for others, the guidelines should follow some sort of weighted average technique. Finally, the fume characteristics of the explosives need to be determined. This would involve determining which types of explosives generate less, or more, toxic fumes than others, and what parameters affect the detonation of the explosives.

The research to develop safer blasting agents and procedures has been progressing steadily towards its final goal of recommending alternative explosives and procedures for blasting in the presence of flammable gases and/or combustible dusts. With continued experimental testing and full-scale validation tests in operating mines, new low incendive blasting agents and procedures will continue to be developed to reduce the probability of gas and/or dust ignitions during underground non-coal mining blasting operations.

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1.— Schematic of the cannon gallery positioned within the gallery.

2.— Photograph of dust ignited by unstemmed ANFO at the LLCG,
showing flame exiting both ends.

3.- Photograph of the Crawshaw-Jones apparatus showing cannon and gas collection chamber.

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