Explosion evaluation of mine ventilation stoppings

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ABSTRACT: The National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) conducted joint research to evaluate explosion blast effects on mine ventilation stoppings at the NIOSH Lake Lynn Experimental Mine (LLEM). After mine explosion accidents, MSHA conducts investigations to determine the cause(s) as a means to mitigate or eliminate future occurrences. As part of these post-explosion investigations, the condition of underground stoppings, including the debris from damaged stoppings, are documented as evidence of the strength and the direction of the explosion forces. The LLEM data showed that a total pressure of 52 kPa (7.6 psi) destroyed the solid concrete block stopping, ~36 kPa (~5.2 psi) destroyed the hollow-core concrete block stopping, and 9 kPa (1.3 psi) destroyed the steel panel stopping. These results will assist investigators in determining the explosion forces that destroy or damage stoppings during actual coal mine explosions.

1 INTRODUCTION

Permanent stoppings are utilized to control and direct the ventilation air flow through underground coal mines to dilute and render harmless methane, entrained coal dust, and other contaminants at the working face and other areas of the mine. The Ventilation controls section (§ 75.333) of Title 30 Code of Federal Regulations (30CFR) requires that permanent stoppings be built and maintained between intake and return air courses beginning at the third connecting crosscut outby the working face, and separate other air courses and direct air as specified. To perform the intended function and meet the requirements of 30 CFR § 75.333, permanent stoppings are to be constructed in a traditionally accepted method and of materials that have been demonstrated to perform adequately or in a method and of materials that have been tested and shown to have a minimum strength equal to or greater than the traditionally accepted in-mine controls. A few examples of traditionally accepted (Federal Register Preamble 1996) stopping construction methods are as follows: 1) 20-cm and 15-cm (8-in and 6-in) concrete block (both hollow-core and solid) with mortared joints; 2) 20-cm and 15-cm concrete blocks, dry-stacked and coated on one or both sides with a strength enhancing sealant suitable for dry-stacked stoppings; and 3) steel stoppings (minimum 20-gauge) with seams and perimeter sealed with a suitable mine sealant.

Unlike mine ventilation seal structures (30CFR §75.335; Greninger et al. 1991, Mitchell 1971, Weiss et al. 2002) that are commonly used to isolate unused sections of a mine, stoppings are not intended to withstand even moderate explosion overpressures. Unfortunately, mine explosions do occur. Depending on the location and severity, explosions can result in fatalities and injuries to underground mining personnel, and cause considerable damage underground to equipment and structures. MSHA personnel conduct investigations of these explosion accidents to determine the root cause(s) as a means to mitigate or eliminate future occurrences. As part of these post-explosion investigations, the location and condition of underground structures and debris are mapped. This information assists in determining the strength and the direction of the forces of the explosion.

The research evaluations at the LLEM involved various full-scale stoppings subjected to known overpressures generated from methane and/or coal dust explosions. Since the construction details and explosion pressure forces were known for these tests, the post-explosion observations and data will be useful for future investigations of mine explosion accidents.

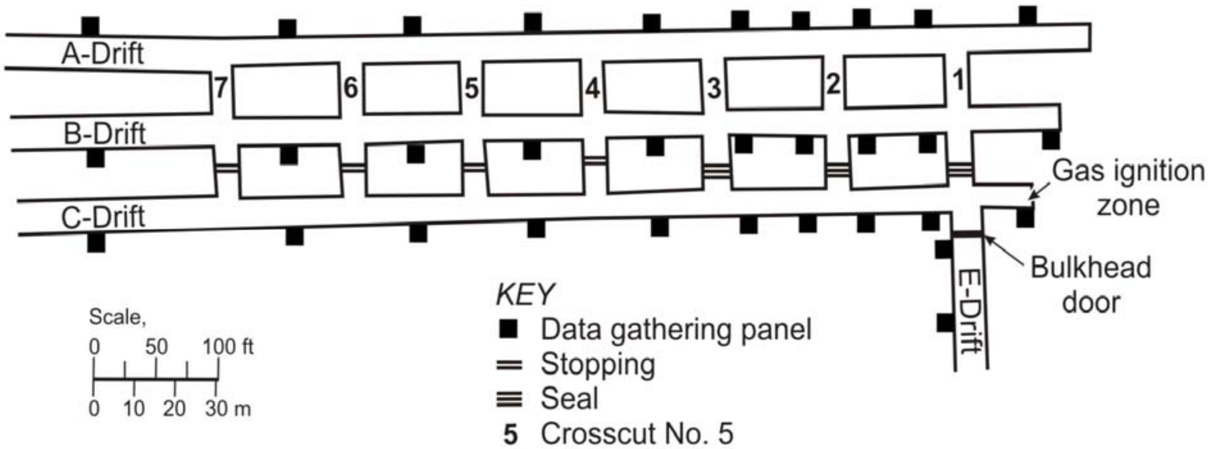

Figure 1. Plan view of the Lake Lynn Experimental Mine showing multiple entry area and stopping locations

2 EXPERIMENTAL MINE AND TEST PROCEDURES

The explosion evaluation tests on the various permanent stoppings were conducted within the experimental mine at Lake Lynn Laboratory (Mattes et al. 1983, Triebsch & Sapko 1990). Lake Lynn Laboratory is located about 80 km (50 miles) southeast of Pittsburgh, near Fairchance, Fayette County, PA, and occupies more than 1.6 km^2 (400 acres) at a former limestone mine.

The LLEM consists of nearly 2,300 m (7500 ft) of underground mine entries developed for mining research. Figure 1 shows an expanded view of the stopping test area in the multiple-entry section of the LLEM. The faces, or closed ends, of A-, B-, and C-drifts are at the right of the figure. The three drifts are each about 520 m (1700-ft) long and extend far to the left of the portion shown in the figure. The stoppings were built in the crosscuts between B- and C-drifts, and the test explosions were ignited in C-drift. The permanent stoppings were constructed in crosscut 4 (X-4) at 108 m (355 ft), X-5 at 138 m (452 ft), X-6 at 168 m (550 ft), or X-7 at 198 m (649 ft) from the face of C-drift. Each of the crosscuts is approximately 6.1 m wide by 2.2 m wide (20.0 ft wide by 7.3 ft high) with a cross-sectional area of about 13.4 m^2 (145 ft^2). Explosion-resistant seals from a previous study were located in X-1 through X-3. Before each explosion test, a 60-t pneumatically operated, track-mounted, concrete and steel bulkhead was positioned across E-drift to contain the initial explosion pressures within C-drift.

Most of the tests utilized a ~9% methane-air concentration within a 3-m-deep by 3.7-m-wide (10-ft-deep by 12-ft-wide) ignition zone (~27 m^3 or ~955 ft^3) contained in the C-drift face area with a clear plastic diaphragm (Fig. 1). An explosion-proof fan mixed the natural gas and air prior to ignition. Electrically activated matches located at the face (closed end) or outby the face within the gas ignition zone, depending on the explosion overpressure desired, were used to ignite the flammable natural gas and air mixtures. In some of the tests, shelves of coal dust were located within a distance of 3 to 12 m (10 to 40 ft) from the face as a means to increase the explosion overpressures.

Pressure transducers were mounted in every data gathering panel in A-, B-, and C-drifts. The pressure transducers of particular interest for these stopping evaluations were along the C-drift rib at 93, 123, 153, 182, and 231 m (304, 403, 501, 598, and 757 ft) from the face at the data gathering panel positions shown in Figure 1. These rib transducers were perpendicular to the direction of the propagating explosion, and therefore measured static pressures. There was also a pressure transducer mounted on the C-drift side of each of the stoppings. These transducers faced the explosion forces propagating into the crosscut, and measured the total pressure (static plus dynamic) at the stoppings. The static pressure is the pressure that is exerted in all directions; the dynamic pressure is the pressure associated with the explosion wind or gas flow. Attached at the center (mid-height and mid-width) of the B-drift side of each stopping was a linear variable differential transducer (LVDT) that measured the movement of the center of the stopping during each explosion. A high-speed, PC-based computer data acquisition system collected the data from the various instruments at a sampling rate of 1500 per second. The reported data were averaged over 10 ms.

3 STOPPING CONSTRUCTION

3.1 Concrete block stoppings

Four hollow-core concrete block stoppings were constructed in X-4 through X-7 between C- and B-drifts at the LLEM (Fig. 1). Each stopping was located approximately 1.5 m (5 ft) toward B-drift from the midpoint of the crosscut (approximately 7 m or 23 ft deep into the crosscut, as measured from C-drift). The blocks were 3-core concrete blocks, with nominal dimensions of 15-cm by 20-cm by 40-cm (6-in by 8-in by 16-in). The uniaxial compressive strength of the block material was 13 MPa (1900 psi). A concrete foundation was installed along the width of each crosscut, and a small amount of mortar was used under the first course of block for leveling purposes. The remaining blocks were dry-stacked (no mortar between the block joints) with staggered joints. Wood wedges were used to tighten each block course at the mine ribs. Wood header boards and wedges were used between the top block course and the mine roof to tighten the structure. An approximately 6-mm (¼-in) thick coating of an approved sealant was applied to both sides of the stoppings as shown in Figure 2.

After the completion of the explosion test evaluation and the removal of the first set of stoppings, additional concrete block stoppings were constructed in X-4 and X-5 using solid concrete blocks, with nominal dimensions of 15-cm by 20-cm by 40-cm (6-in by 8-in by 16-in). These stoppings were constructed in the same manner as the previously evaluated hollow-core concrete block stoppings.

Figure 2. Miner applying sealant to concrete block stopping

3.2 Steel panel stoppings

Jack Kennedy Steel Stoppings manufactured by Jack Kennedy Metal Products and Buildings, Inc., (hereinafter referred to as the steel panel stoppings) were constructed within the LLEM as per the written Instruction Guide provided by the manufacturer. (Disclaimer: Mention of any company or product does not constitute endorsement by NIOSH or MSHA). These stoppings consisted of a series of 30-cm wide by 183-cm high by 5-cm thick (12-in wide by 72-in high by 2-in thick) vertical telescoping steel panels (formed from 20 gage galvanized steel sheeting) that could be lengthened or shortened to accommodate roof heights between 1.8 and 3.1 m (72 and 120 in).

The stoppings were constructed on level concrete foundations in X-6 and X-7. Since the LLEM installation required the use of panel heights in excess of 1.5 m (5 ft), three rows of steel angle bars, extending horizontally from one rib to the other, were required as per the manufacturer's Instruction Guide. Figure 3 shows the nearly completed steel panel stopping in X-6 as shown from the B-drift side. The steel angles were positioned into small holes that were cut into each rib. The angle bars were located at 0.6, 1.0, and 1.7 m (22, 39, and 68 in) from the mine floor in accordance with the manufacturer's specifications.

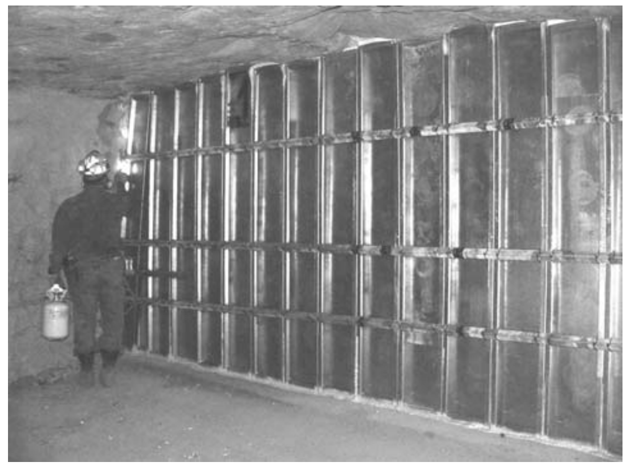

Figure 3. Nearly completed Kennedy steel stopping showing the back side of the panels attached to the horizontal steel angle bars

To start the stopping installation, the first steel panel was installed near the center of the crosscut. As part of the installation, a piece of rigid foam was manually inserted at the top and bottom of each panel to provide a better seal with the roof and floor. Then, a specially-designed installation jack was positioned within the panel's top and bottom grooves and used to exert a roof-to-floor pressure according to manufacturer's specification to temporarily hold the stopping panel in place. A wire twist clamp was fastened around the horizontal rib-to-rib angle, inserted into the inside flanges of the panel, and then tightened. Six clamps were used on the panel to attach it to the three horizontal angles. The temporary jack was then removed from the panel. The steel angles and clamps maintain compression and keep the panels aligned.

After the installation of the center panel, a second panel was then installed against the outby rib, jacked into place, and secured with twist clamps. This process was repeated until all of the panels were installed across the crosscut. The panels were alternated such that the intersection of the telescoping panel sections offset each other. This was accomplished by turning every other panel upside down. Lapover panels were used to cover any gaps between panels, and side extensions were used to cover any large gaps between the panels and the mine rib. A polyurethane sealant was applied to the perimeter on both sides of the stopping and between all of the vertical panel joints on the smooth, or closed panel side (which is the high ventilation pressure side in an actual coal mine installation). All of the steel stoppings were constructed such that the high ventilation pressure side of each stopping was on the C-drift side, which was the side that would be directly impacted by the explosion forces.

4 EXPLOSION TEST RESULTS

4.1 Hollow-core concrete block stoppings

The four hollow-core block stoppings were evaluated in a series of LLEM explosion tests (#427-#434). In test #428, the hollow-core concrete block stoppings in X-4 and X-5 were destroyed by the explosion. The hollow-core concrete block stoppings in X-6 and X-7 showed little damage from this explosion. The pressure traces associated with the stopping in X-4 are shown in Figure 4. The pressure measured by the transducer in front of the stopping is listed as "X-4C, 108 m" and is shown as the solid black curve in the figure. The maximum measured pressure value was 36 kPa (5.2 psi). The pressure traces from the two transducers in the C-drift rib at 92.7 and 122.8 m (304 and 403 ft) were adjusted in time so that the peaks would match that of the transducer in X-4. The interpolated (weighted average) static pressure from these two transducers was 25 kPa (3.6 psi) at the X-4 stopping location. The B-drift pressure behind the stopping was near zero until after the stopping was destroyed.

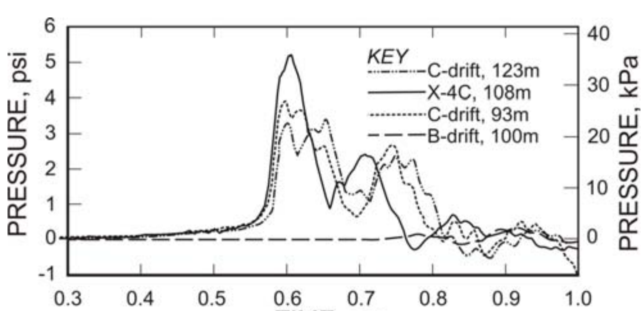

Figure 4. Pressure traces for the block stopping in X-4 during LLEM test #428

The debris field from the destroyed X-4 stopping is shown in Figure 5. The plan view debris map is shown in Figure 6, with whole or partial blocks shown as solid squares and pieces of blocks shown as small x's. The original stopping location between C- and B-drifts is shown by the double horizontal line in the crosscut near the bottom of the figure. Note that these pressure traces, photograph, and debris map for the X-4 hollow-core concrete block stopping are representative of the type of data collected on each of the stoppings during the three evaluation programs described in this paper. The interpolated static pressure was 23 kPa (3.4 psi) at the X-5 stopping that was also destroyed during test #428. The LVDT data showed that both the X-4 and X-5 stoppings moved more than 8 cm (3-in or the maximum displacement that can be measured by the sensor) as they were destroyed.


Figure 5 – Debris from block stopping in X-4 after LLEM test #428, looking toward B-drift

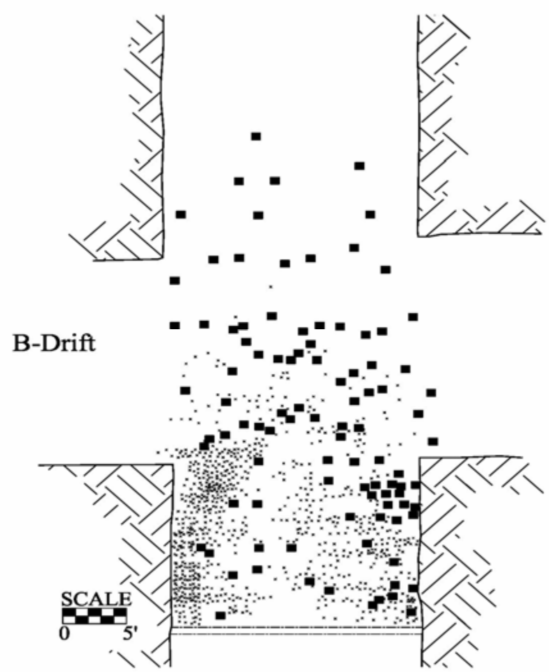

Figure 6. Plan view debris map for the X-4 stopping after LLEM test #428, with original stopping location shown by double line near bottom of figure

The pressure data recorded for the intact hollow-core concrete block stopping in X-6 showed an interpolated static pressure of 22 kPa (3.2 psi); the LVDT showed almost no movement of this stopping. At the intact stopping in X-7, the total pressure was 23 kPa (3.4 psi), the interpolated static pressure was 20 kPa (2.9 psi), and the LVDT showed a movement of less than 0.5 cm (0.2 in).

4.2 *Steel panel stoppings*

The two steel panel stoppings in X-6 and X-7 were evaluated during a series of two LLEM explosion tests (#457-#458). During test #457, there was little or no observable damage to either of the steel panel stoppings. Both the total and static pressures were ~6 kPa (~0.8 psi) at the steel panel stoppings in X-6 and X-7. The pressures in B-drift behind the stoppings were negligible. The LVDT showed ~1 cm (~0.4-in) maximum displacement for the two steel panel stoppings, but returned close to its original position after the explosion.

During test #458, the steel panel stoppings in X-6 and X-7 were destroyed by the explosion. The maximum total pressure measured at X-6 was 9 kPa (1.3 psi). The interpolated static pressure was 8 kPa (1.2 psi) at the X-6 stopping location. The B-drift pressure behind the stopping in X-6 was near zero until after the stopping was destroyed. The debris from the destroyed X-6 steel panel stopping is shown in Figure 7. The stopping in X-6 was displaced from its original position as a unit.

Figure 7 – Debris from the X-6 steel panel stopping after LLEM test #458, looking toward B-drift

Similar pressure data were collected for the steel panel stopping in X-7. The total pressure at the stopping in X-7 was 9 kPa (1.25 psi), and the interpolated static pressure was 8 kPa (1.2 psi). After the test, one side of the X-7 stopping was still partially attached to the outby rib, but the remainder of the stopping was on the floor.

4.3 *Solid concrete block stoppings*

The two solid-concrete-block stoppings in X-4 and X-5 were evaluated during a series of seven explosion tests (#457-#463). During test #460 (fourth explosion test against these stoppings), the total pressure was 46 kPa (6.7 psi) and the static pressure was 31 kPa (4.4 psi) at the X-4 solid-block stopping. At the X-5 solid-concrete-block stopping, the total pressure was 33 kPa (4.7 psi) and the static pressure was 26 kPa (3.8 psi). The LVDT's showed movements of about 3 cm (1.2 in) for the X-4 stopping and about 2 cm (0.8 in) for the X-5 stopping. These maximum LVDT displacements were recorded ~0.02 s after the occurrence of the peak total pressures on each stopping. After the explosion test, both stoppings were essentially intact. However, pronounced cracking was evident on the X-4 stopping between the first and second block course, with a 1.3- to 2.5-cm (½- to 1-in) total displacement of the entire second block course toward B-drift. Additional horizontal cracking above the entire top block course was noted, and a hairline crack extended nearly rib-to-rib across the centerline of the stopping. For the X-5 stopping, a pronounced crack was observed between the first and second block courses with a 0.6 cm (¼-in) displacement of the entire second course toward B-drift.

During test #461, the pressures were not higher than during test #460, and no significant additional damage was observed. During test #462, the total pressure was 52 kPa (7.6 psi) and the static pressure was 39 kPa (5.7 psi) at the X-4 solid concrete block stopping. This stopping was essentially destroyed. Most of the stopping blocks were scattered to and beyond the B-drift intersection. At the X-5 block stopping, the total pressure was 46 kPa (6.7 psi) and the static pressure was 38 kPa (5.5 psi). The stopping withstood the pressure pulse. The X-5 stopping exhibited a more pronounced horizontal crack between the first and second block courses, with an approximately 1.3 cm (½-in) displacement of the entire second block course toward B-drift. A new hairline crack extending from the right center of the stopping to the outby floor corner was also evident. At the center of the X-5 stopping, the LVDT showed movement of slightly over 2.3 cm (0.9 in) during the explosion, but returned close to its original position after the explosion.

A summary of the explosion pressure data for the various stoppings is shown in Tables 1 and 2. Note that for all of these stopping evaluations, the failure pressures are based on the construction conditions and explosion tests within the non-yielding limestone strata at the LLEM. Stopping strengths in mines may vary from these LLEM results when the stoppings are constructed in a coal

Table 1 – Static Pressures Necessary to Destroy Stoppings

Stopping Type	Static Pressure at which stopping survived		Static Pressure at which stopping was destroyed	
	kPa	psi	kPa	psi
Kennedy Metal	6	0.8	8	1.2
Hollow-Concrete-Block	22	3.2	23	3.4
Solid-Concrete-Block	38	5.5	39	5.7

Table 2 – Total Pressures Necessary to Destroy Stoppings

Stopping Type	Total Pressure at which stopping survived		Total Pressure at which stopping was destroyed	
	kPa	psi	kPa	psi
Kennedy Metal	6	0.8	9	1.3
Hollow-Concrete-Block	~23	~3.4	~36	~5.2
Solid-Concrete-Block	46	6.7	52	7.6

seam and if subjected to roof convergence and/or floor heave.

5 CONCLUSIONS

NIOSH and MSHA conducted full-scale evaluation studies to determine the explosion pressures required to destroy typical coal mine ventilation stoppings at the LLEM. In summary, a static pressure of 39 kPa (5.7 psi) and a higher total pressure of 52 kPa (7.6 psi) destroyed a typical solid concrete block stopping as installed within the LLEM. In comparison, a static pressure of 23 kPa (3.4 psi) and a higher total pressure of ~36 kPa (~5.2 psi) destroyed a typical hollow-core concrete block stopping. A static pressure of 8 kPa (1.2 psi) and a slightly higher total pressure of 9 kPa (1.3 psi) destroyed the typical steel panel stopping. The results from the recent LLEM evaluations will assist investigators in more accurately determining the explosion forces that destroy or damage stoppings during actual coal mine explosion accidents.

6 DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

7 REFERENCES

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