

Cemented Paste Backfill Geomechanics at the Lucky Friday Mine

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ABSTRACT: Underhand cut-and-fill mining has allowed for safe extraction of ore in many mines operating in weak rock or highly stressed, rockburst prone ground conditions. However, design of safe backfill undercuts poses unique geotechnical challenges that must be addressed by these operations. Hecla Mining Company and the Spokane Mining Research Division of the National Institute for Occupational Safety and Health have worked collaboratively for several years to better understand the geomechanics of cemented paste backfill (CPB) and thereby improve safety in underhand stopes. This work has included a series of laboratory strength studies and an extensive in situ backfill instrumentation program to monitor long term stope closure and resulting stress in the backfill. The fill must be strong enough to resist flexural failures, but the large stope closures (5 to 10 cm) that occur during undercutting also require the fill to have significant residual strength in order to remain stable after the elastic strain limit has been exceeded. This paper provides an overview of underhand-cut-and-fill mining with CPB as practiced at the Lucky Friday Mine, the collaborative research that has been undertaken with emphasis on the instrumentation and monitoring program, and technical insight that has been gained through this work.

1. INTRODUCTION

Backfilling has allowed for safe extraction of ore in many mines operating in weak rock or rockburst-prone ground conditions. In the Coeur d'Alene mining district of northern Idaho, cut-and-fill mining methods have historically been used to mine narrow, steeply dipping veins of silver-lead-zinc ore (Blake and Hedley, 2003; Williams et al., 2007). At the Lucky Friday Mine, the use of cemented paste backfill (CPB) in conjunction with mechanized underhand cut-and-fill mining methods has reduced the number of injuries and fatalities caused by mining in deep, high-stress, rockburst-prone ground conditions, greatly improving the safety of underground miners (Peppin et al., 2001; Pakalnis et al., 2005).

Although the use of backfill has a sound safety record, implementation of a backfilling program is not without risk and requires technical oversight, particularly in underhand cut-and-fill mining operations where employees work directly beneath cemented backfill. Design of safe backfill undercuts poses unique geotechnical challenges that must be addressed.

Hecla Mining Company and the Spokane Mining Research Division (SMRD) of the National Institute for Occupational Safety and Health (NIOSH) are working collaboratively to better understand the mechanics of CPB and improve safety in underhand stopes. This work has included a series of laboratory strength studies and an instrumentation program to monitor long term stope closure and resulting stress in the CPB. This paper provides an overview of underhand cut-and-fill mining with CPB as currently practiced at the Lucky Friday Mine, the unique challenges to underhand cut-and-fill mining with CPB at depth, and the instrumentation program that has been implemented to monitor stope closure and the resulting backfill pressure.

2. THE LUCKY FRIDAY MINE

The Lucky Friday Mine, located approximately 1.6 km (1 mile) east of Mullan, ID (Figure 1), has been owned and operated by Hecla Mining Company since 1958. Lucky Friday is currently the oldest and deepest operating mine in northern Idaho's Coeur d'Alene mining district and uses underhand cut-and-fill stoping to produce an average 725 t/day from narrow, sub-vertical

lead-zinc-silver veins at depths currently around 2,300 m (7,500 ft) below ground surface. Recent completion of a new 1,140-m (3,700-ft) winze, the No. 4 Shaft (Sturgis et al., 2017), has extended the mine to just over 2,900 m (9,500 ft) below ground surface making it the third deepest operating mine in the western hemisphere (Alexander et al., 2018).



Figure 1. Map showing the location of the Lucky Friday Mine in the Northern Idaho Panhandle near the Montana state line.

3. GEOLOGY AND STRESS CONDITIONS

Historically, the principal ore-bearing structure at the mine was the Lucky Friday vein, however production began in 1997 from several mineralized veins in the Gold Hunter property located about 1,500 m (5,000 ft) northwest of the original Lucky Friday workings. The upper Gold Hunter deposit is hosted in the Wallace formation of the Precambrian Belt Series and transitions into the St. Regis formation below the 5900 level at a depth of about 2,070 m (6,800 ft) below ground surface. The lithology of the Wallace formation consists of weak, highly foliated argillite, argillite alternating with silt caps, and siltite. The argillites of the transitional St. Regis formation below the 5900 level have increasing silt and quartzite content relative to those above this level.

The Gold Hunter deposit lies between two west-northwest trending district faults, which are separated horizontally by about 1,500 m, and consists of a system of several definable veins striking west-northwest and dipping 80° to 90° south, parallel to foliation. Most of the production is from the 30 vein—a composite of closely spaced veins and veinlets averaging more than 1.2 m (4 ft) in width. Development workings and the current extent of mining in the 30 vein are shown in Figure 2.

The argillite host rock and the vein rock have an average intact rock strength of about 100 MPa (15,000 psi), ±35 MPa (±5,000 psi). The major in situ stress is

horizontal, oriented northwest, and having a magnitude of about 1.5 times the vertical stress (Whyatt et al., 1995). As a result, the stress magnitude is comparable with deep, South African gold operations (Alexander et al., 2018).

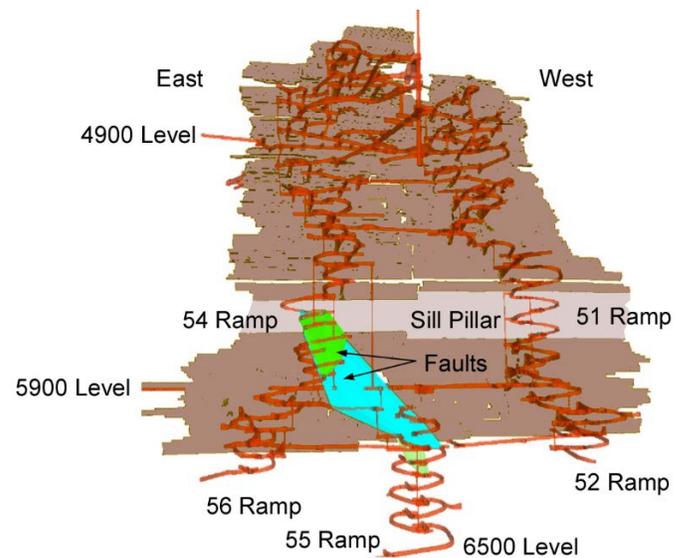


Figure 2. Longitudinal view of the Gold Hunter development workings (red), backfilled stopes (brown), and faults (blue and green).

4. MINING METHOD

In the Gold Hunter deposit, a series of slot drifts are driven perpendicular to the ore body from access ramps on the footwall (north) side of the vein. An undercut stope is mined horizontally in the vein for a distance of about 180 to 200 m (600 to 700 ft) on either side of the slot drift. Five successive underhand cut-and-fill stopes are usually mined from each slot drift as illustrated in Figure 3.

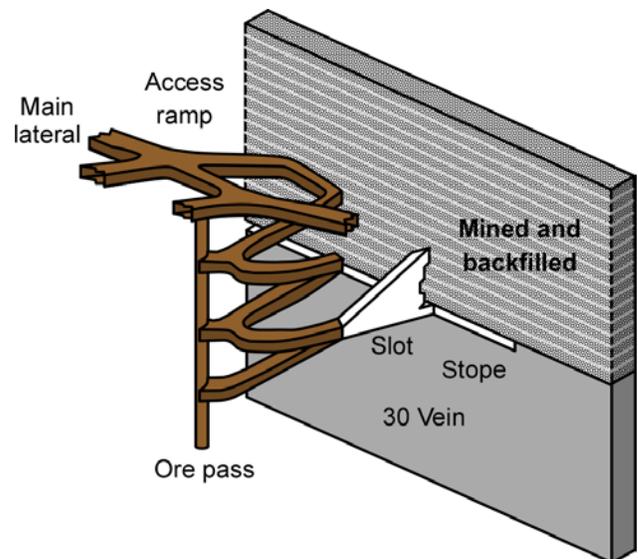


Figure 3. Conceptual diagram of the underhand cut-and-fill mining method practice at the Lucky Friday Mine.

After an undercut stope is excavated, a layer of broken rock or “prep muck” with a thickness of 0.4 to 0.6 m (1.5 to 2 ft) is spread on the floor of the stope. No. 7

DYWIDAG bolts, 1.8 m (6 ft) in length, are driven vertically into the loose muck on roughly a 1.2-m by 1.2-m (4-ft by 4-ft) square pattern to retain potential slabs that may form as the fill is compressed by wall closure. The bolts are fitted with steel plates and nuts and wired together as shown in Figure 4.



Figure 4. Preparing 5550-level, 11-stope east for backfilling.

Classified mill tailings are mixed with 8%–10% binder (25% cement and 75% finely ground, granulated blast furnace slag) at a surface batch plant and gravity delivered in a paste-like consistency to the stope via an underground pipeline distribution system. To contain the paste backfill during placement, a wooden fill fence is constructed across the width of the stope, limiting the lateral extent of the backfill pour to about 46 m (150 ft) and restricting the depth of the pour to about 90% of the stope height. This backfilling process creates a backfill beam, having a thickness of about 3 m (10 ft), and leaving a void or gap, approximately 0.3-m (1-ft) in height, between the upper surface of the backfill pour and the bottom surface of the previously filled cut (Figure 5).



Figure 5. Photograph showing 0.3-m (1-ft) gap between consecutive backfilled levels in the 6350-level, 15-stope.

After the east and west stopes on either side of the slot drift have been backfilled, the paste is allowed to cure and

gain sufficient strength. A subsequent undercut stope is then mined in the vein beneath the newly formed backfill beam (Figure 6). Loose muck that was placed on the floor of the previous cut protects the fill during blasting and falls away from the back as the heading is advanced. To support the CPB back, chain-link mesh is installed overhead using the exposed DYWIDAG bolts and additional friction bolts as needed. Additional rock bolts and mesh are installed to support the stope walls. The CPB, bolts, and mesh thus form a stable reinforced back under which mine personnel can safely work (Figure 7).

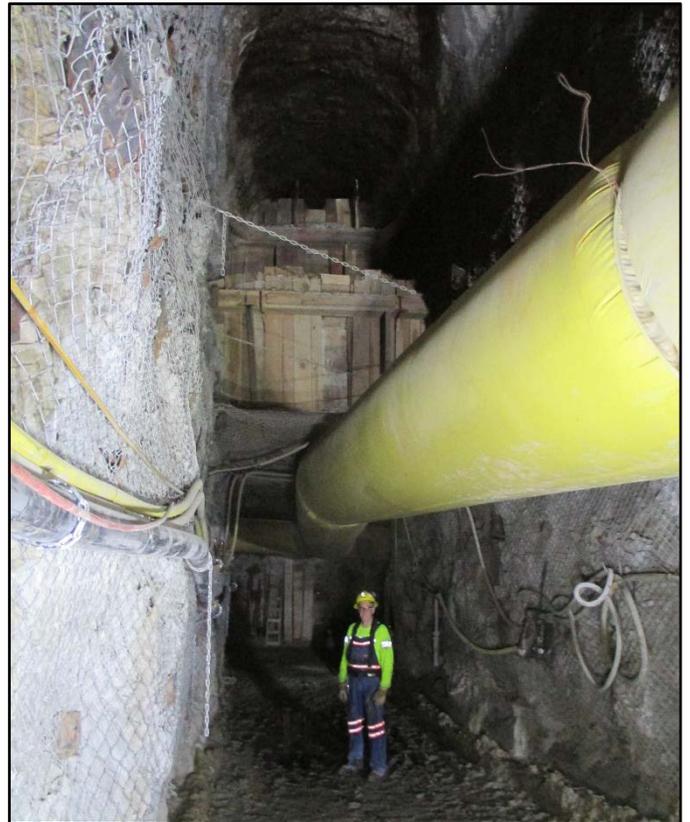


Figure 6. Photograph in 6350-level, 32-slot showing current cut and remaining fill fences from the two backfilled cuts above.



Figure 7. Photograph in 6350-level, 12-stope east showing reinforced CPB back.

5. STABILITY CONSIDERATIONS

To design safe undercut spans, engineers must ensure that the emplaced strength of the backfill exceeds the strength required to support its own weight and resist applied loads from the surrounding rock mass. Strength requirements are typically determined by a combination of analytical formulae (Mitchell, 1991), empirical design (Pakalnis et al., 2005), and numerical modeling. The CPB mix (water content, binder content, tailings gradation, and additives) must result in a product with desired workability while meeting the design strength requirements. Due to the grain size of paste (minus 100 μ m), laboratory test results on 4-in-diameter test cylinders are considered indicative of in-place strength.

Backfill failures in U.S. mines are usually attributed to inadequate backfill strength, insufficient or inconsistent quality control measures, or larger than expected mining spans (Seymour et al., 2013). Span design must consider a combination of failure modes including (1) caving (2) sliding, (3) flexural, and (4) rotational failure (Mitchell, 1991) with consideration of the properties of the fill, stope geometry, loading conditions, stope closure, support, and other factors resulting from filling practices such as cold joints and gaps between successive lifts (Pakalnis et al., 2005). In the absence of rotational instability and closure stresses, flexural stability has been found to be the most critical failure mechanism (Stone, 1993; Pakalnis et al., 2005). The following sections discuss the importance of factors that influence CPB stability at the Lucky Friday Mine.

5.1. Backfill Mix Design and Strength

The mix designs used for underhand stopes are provided in Table 1. The 28-day unconfined compressive strength (UCS) requirement is 2.8 MPa (400 psi), while typical strengths measured at the mine batch plant average >3.4 MPa (>500 psi).

Table 1. Typical CPB Mix Designs

Mix	Binder Content ¹	Water/Cement
General stope fill	8%	3.3
Intersection mix	10%	3.3

¹25% Portland cement, 75% blast furnace slag

Underground coring of CPB and cores from large specimens of backfill brought to surface indicate similar in-place strengths (Emery, 2014; Johnson et al., 2015), if not slightly greater, probably owing to increased curing temperatures underground. The tensile strength, measured by Brazilian and splitting tests, is typically about 10% of the UCS. Emplaced density is around 2050 kg/m³ (130 lb/ft³) with a porosity of 35%–40%.

5.2. Rotational, Sliding, and Caving Stability

Rotational failure cannot occur in narrow, vertical or near-vertical stopes, and therefore does not need to be

considered at Lucky Friday. Sliding failure is kinematically possible, but has never occurred at the mine. Consideration of the Mitchell equation for sliding stability (equation 1) demonstrates why this is the case.

$$(\sigma_v + d \cdot \gamma) > 2 \left(\frac{\tau_f}{\sin^2(\beta)} \right) \left(\frac{d}{L} \right) \quad (1)$$

where,

σ_v = Vertical stress from loading above the sill,

d = Thickness of the sill

γ = Unit weight of the paste fill.

τ_f = shear strength of fill/rock contact

β = Stope dip angle, and

L = Span of the stope

Assuming rough stope walls, sliding failure would require mobilization of the paste shear strength. Conservatively assuming shear strength is due only to cohesion and neglecting normal stress yields factors of safety well in excess of 100 for typical stope geometries and fill strengths as low as 200 psi. Any horizontal pressure on the fill from stope closure further increases stability.

Likewise, caving stability—a function of fill tensile strength and span width—is also not of concern. The Mitchell equation that governs the caving stability of the fill is provided by:

$$L \cdot \gamma > 8 \frac{\sigma_t}{\pi} \quad (2)$$

where,

L = Span of the stope,

γ = Unit weight of the paste fill, and

σ_t = Tensile strength of the paste fill.

For typical stope widths, assuming a tensile strength equal to 10% of UCS results in safety factors well in excess of 20, even for a low strength fill (200 psi UCS).

5.3. Flexural Stability

Flexural stability is of primary concern in the slot intersections, before significant undercutting of the previous backfilled stope. This is because the slot intersection is typically the widest open span (up to 20 ft diagonally), with initially little closure occurring before mining out the cut. The Mitchell flexural stability equation can be used to calculate factors of safety for paste fill beams:

$$\left(\frac{L}{d} \right)^2 > \frac{2(\sigma_t + \sigma_c)}{\sigma_v + d \cdot \gamma} \quad (3)$$

where,

L = Span of the stope,

d = Thickness of the sill,

σ_t = Tensile strength of the paste fill,

σ_c = Horizontal confinement stress,

σ_v = Vertical stress from loading above the sill, and

γ = Unit weight of the paste fill.

Figure 8 presents the results of a stability analysis assuming self-weight loading of the CPB beam, a tensile strength of 10% UCS, and neglecting the impact of wall closure, which initially tends to confine the fill and improve its flexural stability.

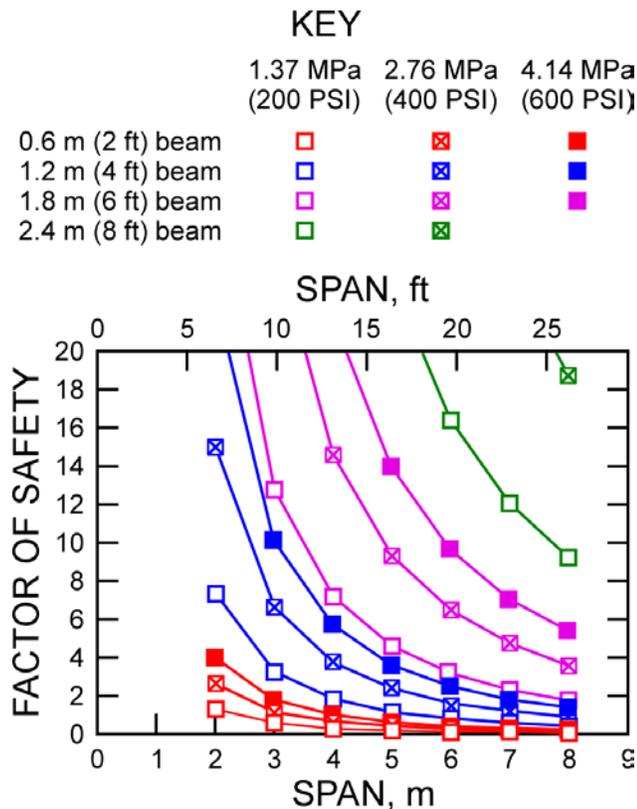


Figure 8. Factor of safety against flexural failure versus span length for paste backfill beams with varying thicknesses and compressive strengths.

The thickness of the backfill beam is the primary factor that determines flexural stability at these limited mining spans. As a result, the stability will be significantly impacted by any factor such as a cold joint that tends to reduce the effective thickness of the beam.

5.4. Mix Design and Quality Control

The quality control of the fill placement process is therefore vitally important to ensuring design strength and prevention of cold joints. Stacking and surging of the paste fill can occur near the outlet of the paste pipeline while filling the stope causing the backfill to be deposited in a discontinuous or intermittent manner. This results in horizontal layering and the formation of cold joints within the overall mass of the paste fill pour. At the Lucky Friday, stacking and surging problems were observed as mining progressed beyond the 5900 level, attributed to premature hydration of the cement binder as a result of very long transport distances in pipelines. As the mining depth increases, the temperature in the rock and underground workings also increases. These higher temperatures at depth in addition to the frictional heating in the long distribution pipelines, may result in acceleration of the cement hydration process, increasing

the viscosity of the paste while degrading its workability and flow characteristics. To prevent stacking and surging, the mine now uses a binder consisting of 25% cement and 75% finely ground, granulated blast furnace slag. The slag has been effective in retarding the hydration process, allowing the workability of the mix to be maintained for the duration of the pour.

Control measures including: monitoring and control of the moisture content of the tailings, schedules for calibrating scales and meters in the batch plant, procedures for sampling and testing the strength of the paste, field tests and procedures for validating flow characteristics and detecting cold joints, training and certification of batch plant operators, and also instructions for documenting, recording, and reporting backfill-related information, are also critical for maintaining good quality control on the final placed product.

5.5. Closure Stresses

A unique challenge to underhand cut-and-fill mining at Lucky Friday is dealing with horizontal stress induced in the CPB as a result of stope wall closure. During undercutting, the stope walls converge in response to the high horizontal ground stresses and compress the CPB. These horizontal loads cause crushing and extensional fracturing near the fill surface shown in Figure 9.



Figure 9. Surface extensional fracturing in cemented paste backfill beam due to horizontal closure.

Results of coring have found that these fractures are primarily horizontal and occur typically within a foot or less of the surface of the beam. While the bolts and chain-link mesh maintain the stability of the underside of the

backfill where personnel are working, the upper surface of the paste fill is unconfined and deforms into the gap above.

The closures encountered in the mine typically exceed the elastic limit of the fill. Therefore, a very brittle fill is to be avoided, and a more ductile fill with significant residual strength is desired.

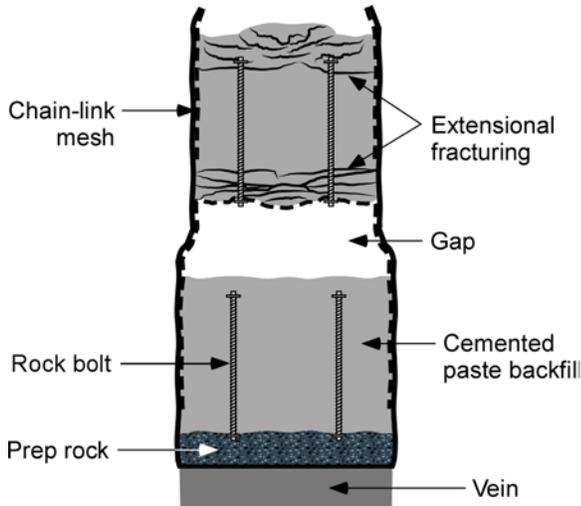


Figure 10. Conceptualized vertical cross section illustrating the progression of horizontal closure as backfill is undercut.

As the underhand mining front continues to advance deeper, the cemented backfill is subjected to further horizontal closure with each additional undercut. This closure eventually compresses the fill. After substantial hangingwall-to-footwall closure, the backfill should in theory behave as a compacting material and begin to strain-harden, gaining stiffness as it is compacted and its void spaces and fractures are compressed. The number of undercuts required to initiate this strain-hardening process will depend on the porosity of the fill and confinement.

6. BACKFILL INSTRUMENTATION

To quantify the stability and geomechanics of the CPB in response to stope closure, a systematic instrumentation approach was developed using robust and reliable instruments. Although the design of the instruments is based on previous research by Williams et al. (1992; 2001), the approach has been significantly revised to improve the survivability of the instruments and to provide reliable measurements of stope closure and fill pressure to the mine staff on a nearly real-time basis.

6.1. Instrumentation Design

Custom-designed closure meters were built to measure hangingwall-to-footwall convergence in the backfilled stopes (Figure 11). The body of the closure meter consists of telescoping sections of steel pipe and tubing attached to steel end-plates, which are bolted to the stope walls. Linear position transducers are mounted internally in the closure meter to measure displacement as the stope walls converge. Pressure cells mounted on the

steel anchor plates measure the horizontal change in stress in the CPB.



Figure 11. Typical backfill instrumentation setup used to monitor stope wall convergence and horizontal fill pressure.

Two types of closure meters were fabricated and installed: single-acting closure meters with one position transducer for measuring displacement across the full length of the instrument (hangingwall-to-footwall closure), and double-acting closure meters equipped with a second position transducer for also measuring displacement to a center plate located at the mid-span of the instrument (measuring closure from the hangingwall to the mid-span of the stope).

6.2. Sensor Selection

UniMeasure HX-P510 linear position transducers were chosen to measure stope closure. The position transducer consists of a rotary potentiometer that is encased within an environmentally sealed, waterproof housing. The rotary potentiometer measures a voltage output as a stainless steel wire cable is extended or retracted from the housing. These voltage measurements are in turn converted to displacement units to reflect a change in position of the cable. The selected model has a resolution of $\pm 0.01\%$ and a measurement range of 63.5 cm (25 in).

Backfill horizontal stress is measured using pressure cells mounted directly to the closure meter's steel anchor plates (Figure 12). Geokon Model 4810 contact pressure cells with a measurement range of 0 to 7.5 MPa (1,088 psi) were selected. This type of earth pressure cell is specifically designed to measure soil pressures exerted on a structure.

This instrument consists of two circular stainless steel plates that are welded together around their edges, forming a narrow cavity which is filled with hydraulic oil. A thick back-plate protects the instrument and mounts directly to the structure. A thin front-plate is welded to the back-plate, forming a flexible hinge for increased sensitivity to pressure changes. Pressure applied to the cell induces an equal pressure on the internal hydraulic

fluid that is, in turn, sensed by a vibrating-wire transducer connected to the cavity between the two plates by high-pressure stainless steel tubing. A measurement of the change in the frequency of the vibrating wire is converted to pressure using a calibrated gage factor supplied by the manufacturer. The pressure cell is also equipped with a thermistor to help account for the influence of changes in temperature on the instrument's readings.

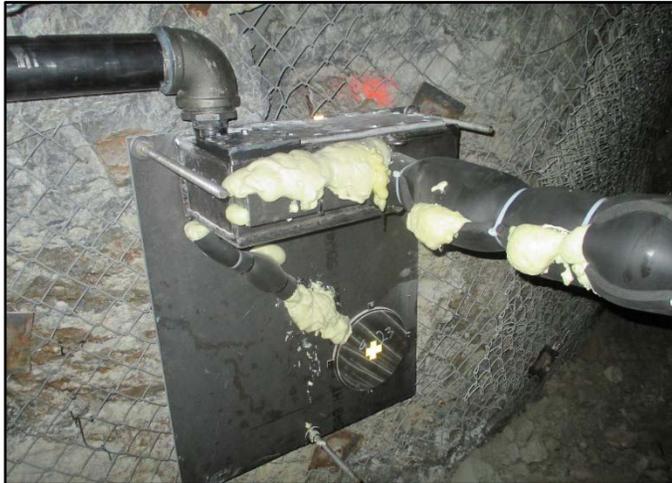


Figure 12. Contact pressure cell mounted on a closure meter anchor plate.

6.3. Data Acquisition and Storage

The closure meters and pressure cells are monitored every two hours by Campbell Scientific data acquisition systems (DAS) located at substations in nearby slot drifts. A typical DAS consists of the following components: CR1000 data logger, AVW200 vibrating wire analyzer, AM16/32B multiplexers, and various communication interfaces, depending on the specific link to the mine's communication system—either a fiber optic cable or a leaky feeder radio. Both of these systems are linked to a computer server at the surface.

The DAS can be accessed remotely, and the instrument data can be viewed on Hecla's corporate intranet website by mine management and NIOSH researchers on an almost real-time basis. This allows the instrument data to be used by mine staff for daily operational decisions or safety concerns, and to be remotely monitored for maintenance and timely repairs.

7. STOPE MONITORING SITES

To date, closure meters and pressure cells have been installed, prior to backfilling, at eleven monitoring locations in three 30-vein production stopes: 5550-level, 11-stope immediately above the west side of the large sill pillar shown in Figure 2; the 6350-level, 15-stope; and 6350-level, 12-stope located on a deeper mining horizon beneath the sill pillar. The 11 and 15-stope instruments are the focus of this paper as the 12-stope instruments were only recently installed and have not yet been undercut.

The 11-stope instruments were installed in September and October of 2014, whereas the 15-stope instruments were installed in March of 2016. To avoid interfering with the production crews, the 11-stope instruments were installed after the fifth and final cut had been mined from the slot drift. Modifications to the instruments and their installation procedures allowed the 15-stope instruments to be installed during the second cut, while production crews were preparing the stope for backfilling. As shown in Figures 13 and 14, closure meters (CM) and pressure cells (PC) were installed at four separate locations in each stope. Stope width at the measurement sites varied from 2.73 to 4.11 m, but averaged about 3.4 m (11 ft).

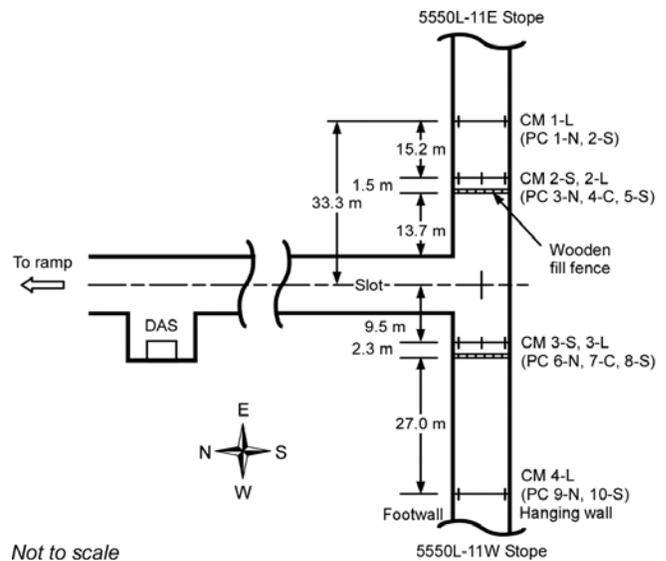


Figure 13. Plan view of 5550-level, 11-stope backfill instrumentation sites.

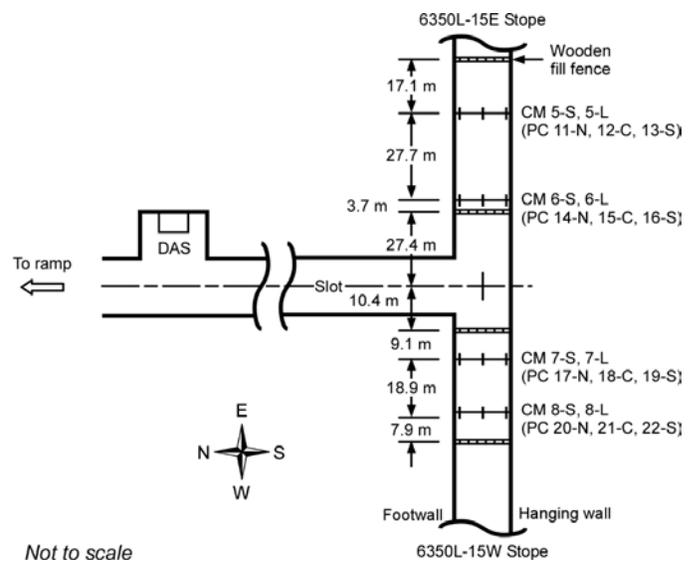


Figure 14. Plan view of 6350-level, 15-stope backfill instrumentation sites.

8. STOPE CLOSURE

Figure 15 shows typical measured closures from one of the monitoring sites. The approximate undercut start

times are indicated on the figure by vertical dashed lines. With each undercut mining advance, the full-span closure meters generally measured a consistent increase in stope closure, averaging about 7.6 cm (3 in). The half-span closure meter measurements were a fraction of the total closure, but varied from site to site. Most of the stepped increase in closure occurred as underhand mining advanced directly below the locations of the instruments.

In 11-stope, a total of five undercut advances were monitored over a period of about two years. Measurements collected from all 11-stope backfill instruments from September 18, 2014 through September 7, 2016 are shown in Table 2, grouped by the monitoring locations noted in Figure 13. Cuts for which data are not entered indicate that the instruments were not providing reliable measurements at the time of that undercut.

Two instruments (CM 1-L, CM 2-S) stopped working shortly after the first undercut. CM 2-L began providing reliable results again during Cut 4. Moisture intrusion is the likely cause of this intermittent behavior. Three instruments (CM 2-S, CM 3-L, CM 4-L) provided

continuous readings through all five cuts. Total measured stope closure ranged from 40 to 50 cm during this period.

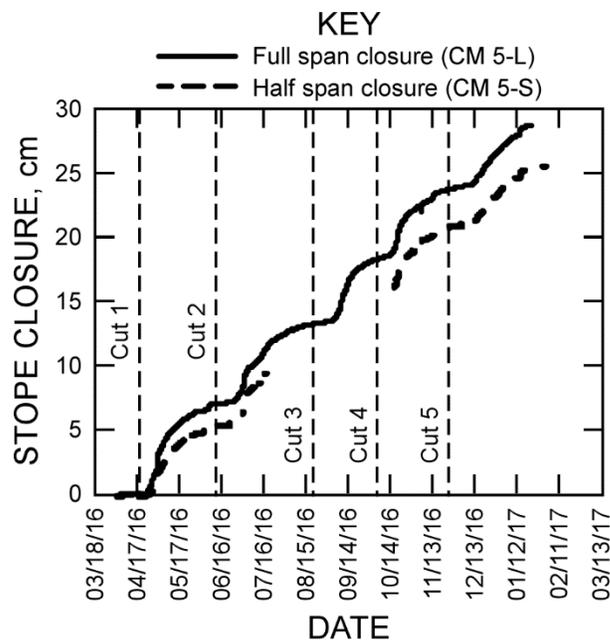


Figure 15. Example stope closure measurements from CM 5-L and CM 5-S in 6350 level, 15-stope, west.

Table 2. Stope closure measurements from 5550 level, 11-stope closure meters

Sensor	Location	Description	Cut 1 (cm)	Cut 2 (cm)	Cut 3 (cm)	Cut 4 (cm)	Cut 5 (cm)
CM 1-L	East	Full-span closure meter	8.18	-	-	-	-
CM 2-S	East	Half-span closure meter	2.52	10.43	16.25	22.01	42.06
CM 2-L	East	Full-span closure meter	6.62+	-	-	31.58	49.16
CM 3-S	West	Half-span closure meter	3.90	-	-	-	-
CM 3-L	West	Full-span closure meter	6.42	15.07	21.89	29.90	43.36
CM 4-L	West	Full-span closure meter	9.72	16.84	23.67	30.64	40.59

Table 3. Stope closure measurements from 6350 level, 15-stope closure meters

Sensor	Location	Description	Cut 1 (cm)	Cut 2 (cm)	Cut 3 (cm)	Cut 4 (cm)	Cut 5 (cm)
CM 5-S	East	Half-span closure meter	5.47	-	-	21.18	25.57
CM 5-L	East	Full span closure meter	7.31	13.47	18.63	24.11	28.77
CM 6-S	East	Half-span closure meter	2.94	7.19	10.35+	-	-
CM 6-L	East	Full span closure meter	6.19	11.90	16.30	22.65	-
CM 7-S	West	Half-span closure meter	2.26	5.38	-	-	-
CM 7-L	West	Full span closure meter	4.55	10.56	17.77	20.07+	-
CM 8-S	West	Half-span closure meter	1.74	3.91	6.63	-	-
CM 8-L	West	Full span closure meter	7.21	13.61	22.02	27.77	33.23

Measurements recorded from the 15-stope backfill instruments from March 18, 2016, to March 13, 2017 are provided in Table 3, grouped by the monitoring locations shown in Figure 14. After almost six months and three

undercut advances, all of the instruments installed in the 15-stope were continuing to function, except CM 5-S and CM 7-S. Five closure meters (CM 5-S, CM 5-L, CM 6-L, CM 7-L, CM 8-L) were able to monitor through Cut 4.

Three instruments (CM 5-S, CM 5-L, CM 8-L) were functioning after Cut 5, measuring as much as 33 cm.

9. HORIZONTAL BACKFILL PRESSURE

Figure 16 shows a typical example of measured horizontal backfill pressures from one of the closure-meter sites. As the first undercut heading is driven beneath the locations of the instruments, the horizontal pressure in the CPB increases rapidly. Loading of the CPB beyond its intact compressive strength occurs shortly thereafter, as depicted by the peaks in the pressure measurements during the first undercut.

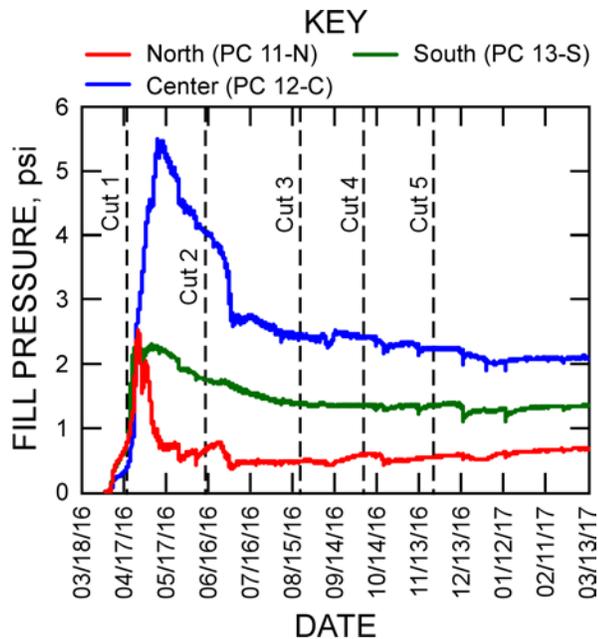


Figure 16. Horizontal backfill pressure measurements from CM 5 monitoring site in 6350 level, 15-stope, west

In 11-stope (Table 4), the maximum horizontal pressure measured during the first undercut ranged from 1.59 to 5.40 MPa (231 to 783 psi) and averaged about 3 MPa (435 psi) for the ten pressure cells. Fill pressure varied depending on the monitoring location in the stope and the specific placement of the pressure cells. The largest fill pressures were generally measured at the mid-span (center) of the stope rather than at the hangingwall (south) or footwall (north), with a few exceptions.

CPB pressure measurements in 15-stope (Table 5) were similar to those of 11-stope, with maximum horizontal pressure measured during the first undercut ranging from 1.85 to 5.50 MPa (269 to 798 psi) and also averaging about 3 MPa (438 psi) for the 12 pressure cells. A significant improvement in instrument longevity compared with 11-stope, especially for the pressure cells is noted. This is attributed to design changes which better protect the instruments and lead-wires.

10. BACKFILL TEMPERATURE

While the 11-stope instruments were initially read manually for several months, the 15-stope instruments were monitored continuously with a data logger before, during and after the pour. This allowed determination of the effects of stope filling and paste curing on the readings.

Temperature changes can significantly affect pressure cell measurements in cemented backfill (Tesarik et al., 2006). As paste is poured and begins to cure, its temperature rises due to hydration of the curing cement. This increase in temperature causes the pressure cells to give a false indication of initial applied stress increase. Although the instrument is supplied with a temperature correction, this correction is for the vibrating wire sensor itself; not the pressure cell bladder and contained oil.

Table 4. Horizontal backfill pressure measurements from 5550 level, 11-stope closure meters

Sensor	Location	Peak (MPa)	Cut 1 (MPa)	Cut 2 (MPa)	Cut 3 (MPa)	Cut 4 (MPa)	Cut 5 (MPa)
PC 1-N	East Side, North Wall	4.04	2.33	1.56	1.05	0.95	-
PC 2-S	East Side, South Wall	3.74	3.03	1.84	-	-	-
PC 3-N	East Side, North Wall	1.78	1.86	1.71	1.71	1.79	3.28
PC 4-C	East Side, Stope Center	3.49	-	-	-	-	-
PC 5-S	East Side, South Wall	5.40	-	-	-	-	-
PC 6-N	West Side, North Wall	2.12	2.15	1.75	1.28	0.64	0.49
PC 7-C	East Side, Stope Center	3.24	-	-	-	-	-
PC 8-S	East Side, South Wall	2.16	-	-	-	0.92	0.91
PC 9-N	East Side, North Wall	1.58	1.18	1.81	-	-	-
PC 9-S	East Side, South Wall	2.07	1.48	1.80	-	-	-

Table 5. Horizontal backfill pressure measurements from 6350 level, 15-stope closure meters

Sensor	Description	Peak (MPa)	Cut 1 (MPa)	Cut 2 (MPa)	Cut 3 (MPa)	Cut 4 (MPa)	Cut 5 (MPa)
PC 11-N	East Side, North Wall	2.54	0.72	0.42	0.56	0.58	0.62
PC 12-C	East Side, Stope Center	5.47	3.74	2.35	2.36	2.21	2.07
PC 13-S	East Side, South Wall	2.29	1.71	1.36	1.32	1.34	1.28
PC 14-N	East Side, North Wall	2.31	1.71	1.33	1.34	1.36	-
PC 15-C	East Side, Stope Center	4.29	2.71	1.62	1.44	1.05	-
PC 16-S	East Side, South Wall	3.04	2.28	1.90	1.98	2.09	-
PC 17-N	West Side, North Wall	1.62	1.88	2.16	2.59	-	-
PC 18-C	East Side, Stope Center	2.99	2.74	2.55	2.48	3.07	4.02
PC 19-S	East Side, South Wall	1.97	1.28	1.40	1.48	1.71	2.33
PC 20-N	West Side, North Wall	1.87	1.11	1.07	0.80	-	-
PC 21-C	East Side, Stope Center	1.96	0.89	0.31	0.63	0.56	0.24
PC 22-S	East Side, South Wall	1.85	1.12	0.91	0.67	-	-

The maximum fill temperature recorded during curing averaged about 49°C (120°F) ranging from 41°C (105°F) to 57°C (135°F). Figure 17 shows a typical response of a pressure cell before, during, and after a pour.

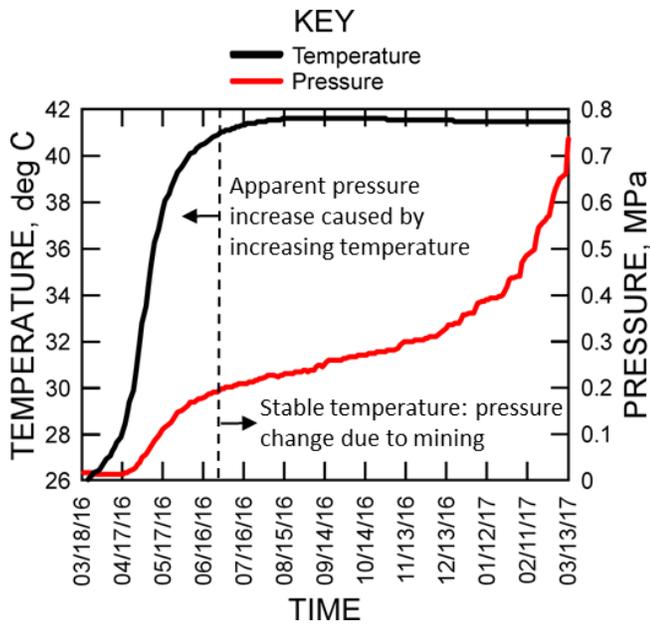


Figure 17. Example temperature and pressure data for a contact pressure cell during and after the paste pour.

Once the stope is filled and the CPB begins to cure, a rapid increase in temperature is observed which then levels off. This rise in temperature is accompanied by an apparent rise in pressure of about 0.2 MPa (30 psi).

After the temperature levels off, pressure changes can be attributed solely to stope closure. The temperature effect is negligible for long-term monitoring because the backfill temperature stabilizes, and the in-place CPB is usually subjected to pressures well in excess of the changes due to temperature.

11. IN SITU STRESS-STRAIN RESPONSE

To further interpret the geomechanical response of the CPB to mining, in situ stress versus strain was plotted using the closure and fill pressure measurements. Many 11-stope instruments stopped functioning after the second undercut making it difficult to construct stress-strain curves for each closure meter. Therefore, stress-strain curves were made for the east and west sides combining surviving instruments. The results are shown in Figure 18.

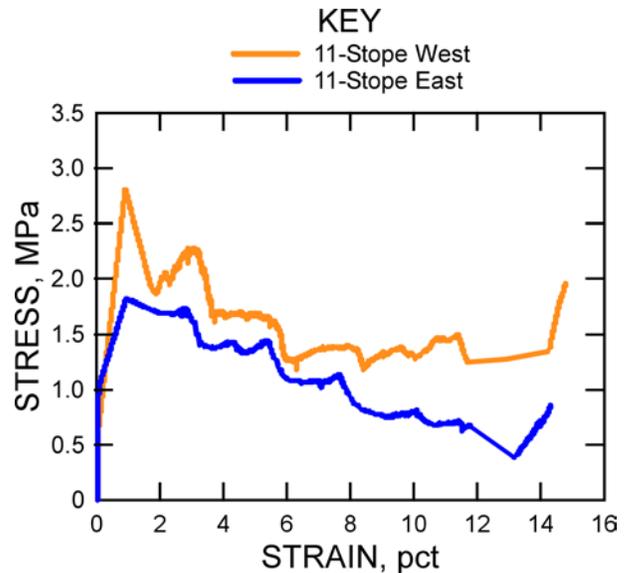


Figure 18. In situ backfill stress vs. strain, 5550-level, 11-stope

The longevity of the 15-stope instruments allowed the in situ CPB stress-strain behavior to be constructed for each of the four 15-stope monitoring sites. Horizontal stress in the paste fill was calculated by averaging the pressure measurements obtained from the three pressure cells at each site, while horizontal strain was computed using the total stope closure data at each site.

While the 11-stope instruments were initially read manually on a weekly basis before the DAS could be set up, the 15-stope instruments were connected to the DAS immediately. As a result, the elastic response of the CPB to undercut mining is clearly indicated by the initial straight-line portion of the stress-strain curves in Figure 19.

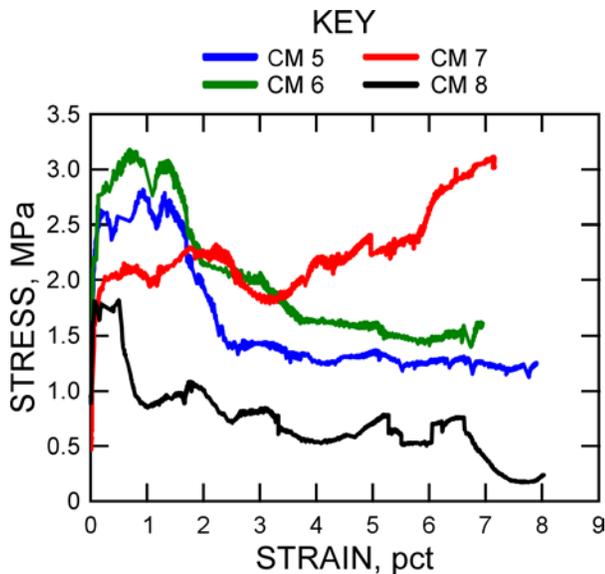


Figure 19. In situ backfill stress vs. strain, 6350-level, 15-stope

Peak strength occurs between 0.5% and 1% strain, consistent with laboratory testing of the fill. For a typical stope width of 3.4 m (11 ft), this represents only about 2.5 cm (1 in) of closure. During the fifth undercut, the backfill in the 11-stope began a pronounced change in behavior with strain hardening occurring between 13% and 14% strain. The 15-stope data show that the fill generally has not yet reached strain levels high enough for hardening to occur.

12. IN SITU DEFORMATION MODULUS

Using the 15-stope data, an average in situ modulus of deformation was determined by analyzing the slope of the stress-strain response over a stress range of 30% to 60% of the average peak strength. The resulting values are shown in Table 6.

Table 6. Measured In Situ Modulus

Monitoring Location	Modulus (GPa, ksi)
CM 5	3.68, 534
CM 6	3.57, 518
CM 7	3.05, 442
CM 8	2.52, 365

The average, 3.2 GPa (464 ksi), is comparable to in situ modulus of deformation values reported by Williams et al. (2001) for CPB used in the old Lucky Friday vein,

which ranged from 0.68 to 5.09 GPa (99 to 739 ksi) and averaged about 2.41 GPa (350 ksi).

The average in situ modulus value is also comparable to the Young's modulus of 2.28 GPa (330 ksi), which was reported by Johnson et al. (2015) for unconfined compression tests on strain-gauged core samples of CPB with an average UCS of 4.1 MPa (602 psi). Although this testing was performed on CPB of a slightly older mix design, the only significant difference was in binder blend (100% Portland cement instead of the cement-slag blend that is currently used), not tailings or binder content. This indicates that fill properties measured from test specimens and in situ are not significantly different for design and analysis purposes.

13. CONCLUSIONS

This paper has discussed some of the issues associated with the use of cemented paste backfill (CPB) in deep, narrow underhand-cut-and-fill stopes at the Lucky Friday Mine. An instrumentation approach developed by NIOSH, in cooperation with the Heck Mining Company, has been successful in monitoring stope closure and the stability of CPB through several stages of underhand cut-and-fill mining. Measurements from these instruments are not only useful for mine design, but they also help confirm observations and justify long-standing assumptions regarding the role of backfill in ground support. This work has shown that:

- Hangingwall-to-footwall closure of about 7.6 cm (3 in), on average, occurs with each successive undercut.
- Maximum horizontal fill pressures during the initial undercut advance average about 3 MPa (435 psi). This exceeds the design UCS requirement.
- A residual strength of 1 to 2 MPa (100 to 150 psi) is maintained over several undercuts, allowing the fill to remain stable even though stope closure exceeds the CPB elastic strain limit.
- An analysis of the in situ stress-strain response indicates an average in situ CPB deformation modulus of 3.2 GPa (460 ksi).
- Both the in situ strength and deformation modulus are comparable to properties derived from laboratory tests on CPB samples. This provides additional confirmation that CPB properties determined by lab-scale tests are representative of the in situ properties. A common assumption made for paste backfills.
- A transition from strain-softening to strain-hardening appears to begin after roughly 13%–14% strain. Additional work is required to confirm this observation.

To ensure safe and productive operation as mining progresses deeper, Hecla is revising the Lucky Friday's mining method and transitioning to tele-remote continuous mechanical excavation, with trial operation of a new mechanical excavator, the Hecla Mobile Miner, planned to begin by early 2020 (Alexander et al. 2018). Backfilling with cemented paste will continue to play a vital role in the new underhand method, and the data from this study provides good baseline information for these and other future changes in mine design.

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DISCLAIMER

The findings and conclusions in this paper are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by NIOSH.

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