Table 2.—Closure readings.

Instrument and location	5660 level, cut 9		5750 level, cut 1		Cuts 9 + 1		5750 level, cut 2		Cuts 9+1+2	
	cm	in	cm	in	cm	in	cm	in	cm	in
Muck bay	0.10	0.04	0	0	0.10	0.04			0.10	0.04
Backfill string pots:										
West 1	7.77	3.06	11.28	4.44	19.05	7.5	12.19	4.8	3.24	12.3
West 2	+4.65	+1.83								
East 1	12.14	4.78								
East 2	3.78	1.49	6.63	2.61	10.16	4.1	3.81	1.5	14.22	5.6
Muck bay	0.08	0.03	0.10	0.04	0.18	0.07				
Gap string pots:										
West 1	12.4	4.88	11.05	4.35	23.44	9.23				
West 2	11.33	4.46								
East 1	16.36	6.44	11.86	4.67	28.22	11.11	9.68	3.81	37.90	14.92
East 2	15.80	6.22								
Slot 1	8.71	3.43								
Tape extensometer:										
Slot 2	6.55	2.58								
West 1	9.12	3.59								
West 2	12.47	4.89								
East 1	6.76	+2.66								

+ = Quit working.

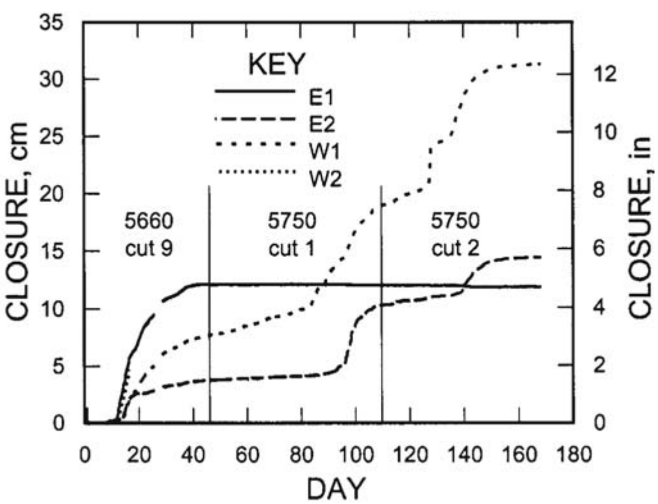

Figure 10.—Backfill closure as a function of time.

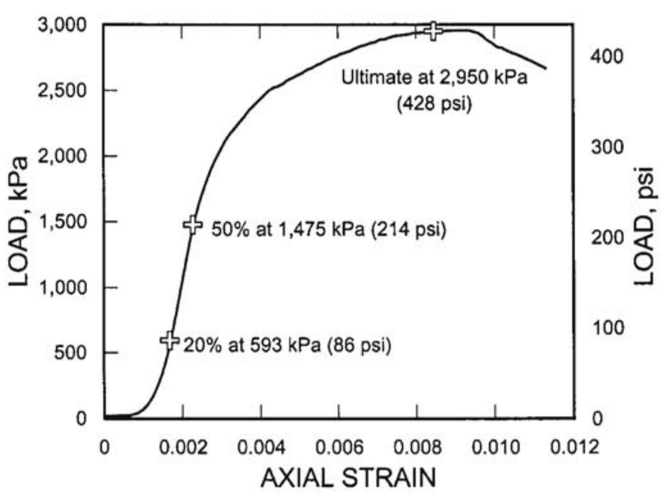

Figure 11.—Compressive test of cemented sandfill, stress/strain curve.

BACKFILL PRESSURE READINGS

Model 3500 earth pressure cells from Geokon, Inc., were placed in the cemented backfill to monitor pressure as the walls closed. The backfill pressure increased rapidly as wall closure commenced (figure 12). The readings peaked with mining of cut 9, after which backfill pressure dropped as each subsequent cut was completed. Peak pressures ranged from a low of 793 kPa (115 psi) in the intersection to 4178 kPa (606 psi) at West 2; the average across the vein was 2757 kPa (400 psi) at 15 days. The data collected in the mine were within the range of the data collected in the laboratory (7-day unconfined compressive strength of 2082 kPa [302 psi] and 28-day unconfined compressive of 3254 kPa [472 psi]).

The 20-50 modului determined at locations E1, E2, W1, and W2 were 681, 1513, 2361, and 5095 MPa (98,760, 219, 400, 342,400, and 738,800 psi), respectively, and averaged 2412 MPa (349,800 psi). Strain was determined by dividing measured wall closure by the original opening width. These modulus values were documented 8 to12 days after the backfill had been poured and as mining of the following cut passed the instrument locations. These data show that the ultimate strength of the cemented backfill was surpassed by loading induced by the large amounts of wall closure experienced in the stope. Thus, rock bolt reinforcement is needed to maintain the integrity of the backfill so that it will be safe for miners to work under.

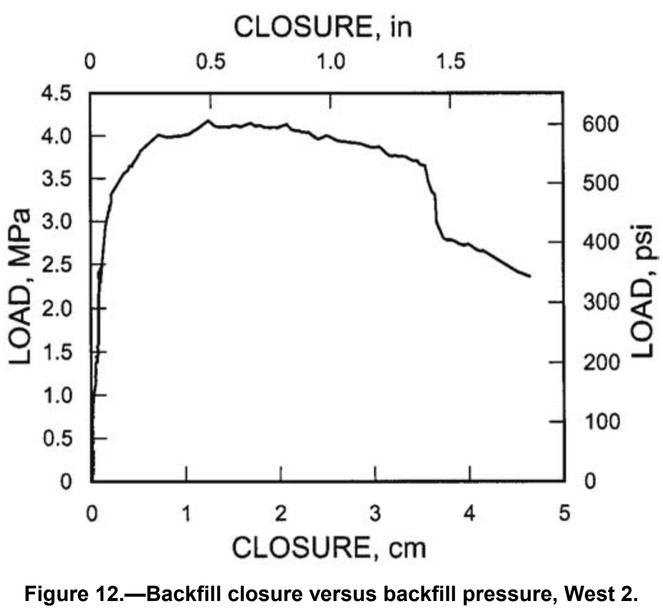

Figure 12.—Backfill closure versus backfill pressure, West 2.

Broken backfill was observed in the chain link below the backfill, and backfill heaving was seen in the gap at the top. The backfill eventually broke up to where it could no longer carry load and support itself. It then collapsed onto the backfill below it. When these collapses occurred, they presented no danger to miners because mining was usually two or more cuts below, and two or more intact backfill horizons were between the miners and the collapsed fill remained.

INSTRUMENTED ROCK BOLTS

The vibrating-wire instrumented rock bolts and load cells were initially calibrated in a Tinius-Olsen testing machine at SRL to 53 kN (12,000 lb); however, readings recorded at the mine with the instrumented rock bolts using the 27-N/Hz (6-lb/Hz) calibration indicated that the yield and ultimate strengths of the rock bolts had been exceeded.

To determine if the initial readings were accurate or if this were a calibration problem, two instrumented rock bolts were tested in tension to failure. The instrumented rock bolts yielded at 160 kN (36,000 lb) and failed between 209 and 221 kN (47,000 and 49,900 lb) at the gauge location.

These tests showed that the hole drilled for the vibrating wire did not affect the yield strength of the bolt, but that it did reduce ultimate strength from 240 to 215 kN (54,000 to 48,450 lb). The slope of gauge response was linear between 8.9 and 124 kN (2000 and 28,000 lb) at 27 N/Hz (6 lb/Hz). Gauge response was then rapidly reduced to 2 N/Hz (0.45 lb/Hz). At 142 kN (32,000 lb), the gauges failed before the yield point of the rock bolts was reached. Figure 13 shows calibration load versus gauge response frequency for the bolts tested to failure. These tests showed that the vibrating-wire gauges installed in the end of the bolts were inadequate for this application and any future tests should use a gauge with a higher load range. The data were reanalyzed using this calibration curve.

Load on six of the nine instrumented rock bolts placed vertically in the backfill exceeded 142 kN (32,000 lb), which was the limit of the vibrating-wire gauge. Information from most of the instrumented rock bolts was eventually lost because deformation of the backfill apparently broke many of the signal wires in the backfill.

The data showed that the vertical reinforcing rock bolts in the backfill did a good job of resisting backfill deformation and provided a safe back for miners to work under. Initial loads began at zero and increased over time, indicating a direct relationship to wall closure.

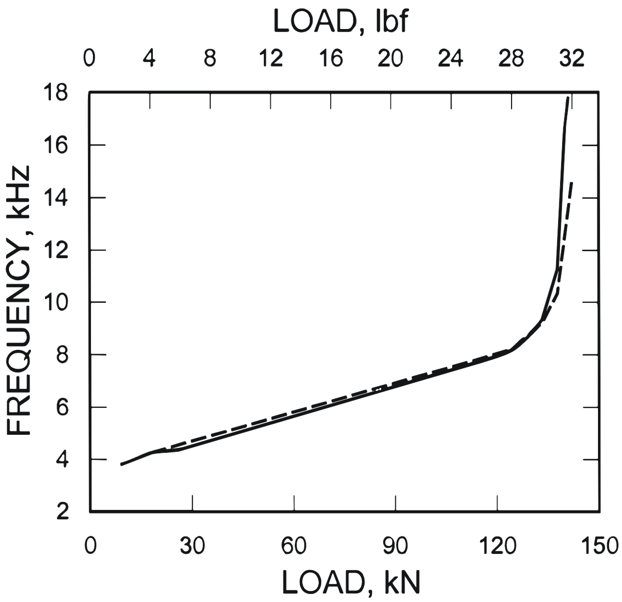

Figure 13.—Calibration curve showing relationship between frequency and load on instrumented rock bolts.

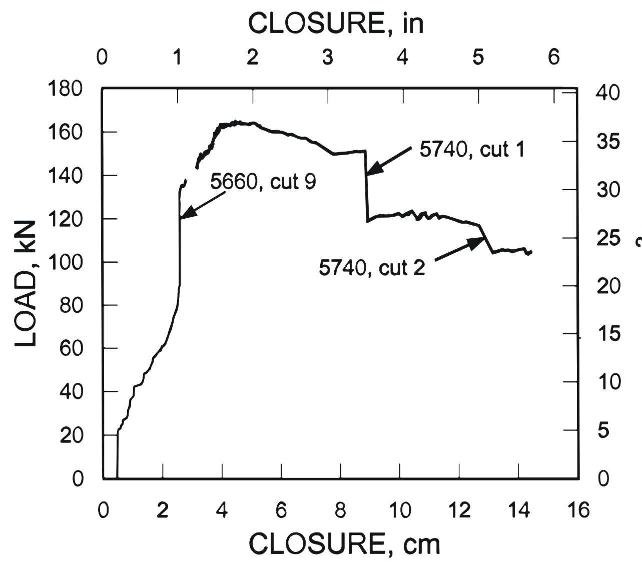

Figure 14.—Backfill closure versus rock bolt load, East 2.

ROCK BOLT LOAD CELLS

Data from the rock bolt load cells indicated that the vertical rock bolts were under loads from 41 to 179 kN (9300 to 40,300 lb) after cut 9 was mined except in the muck bay, where loads ranged from 2.9 to 19.1 kN (660 to 4300 lb). Loads on the vertical rock bolts along the vein dropped as cuts were subsequently mined. This drop was probably a result of the continued breaking up of the backfill as the walls closed. Figure 14 shows the relationship of rock bolt load to backfill closure at East 2. The data indicate rock bolt load leveling off and decreasing as closure continued following each mining cut. This drop was probably caused by backfill failure around the rock bolt bearing plates as the walls converged. Inspection of the bottom of the backfill revealed bags of broken backfill in the chain link fencing between the rock bolt plates. Visual observation of the top of the 2.4-m- (8-ft-) long vertical rock bolts also confirmed that the 15- by 15-cm (6- by 6-in) bearing plates resisted backfill deformation and transferred load to the rock bolt.

Table 3 is a summary of the loads recorded on the instrumented rock bolts and load cells. The readings of 164 and 179 kN (36,900 and 40,300 lb) are the only ones exceeding the yield strength of the rock bolt at 160 kN (40,900 lb); the rest were below the yield strength. This is important because it

Table 3.—Loads on instrumented bolts and load cells for three cuts of mining.

Location	5660-05, cut 9				5750-05, cut 1				5750-05, cut 2			
	Bolt		Load cell		Bolt		Load cell		Bolt		Load cell	
	kN	lb	kN	lb	kN	lb	kN	lb	kN	lb	kN	lb
Vertical bolts:												
Slot	+142	+32,000	102	22,900			44.3	9,960			35.1	7,890
Muck bay	8.9	1,990	0.9	194	6.7	1,510	1.8	400	2.9	655	10.1	2,270
West 1	63.1	14,200	42.5	9,340	503	11,300	34.1	7,680			25.3	5,700
West 2	+142	+32,000	116	26,200			19.4	4,370			9.9	2,230
East 1	+142	+32,000	179	40,300			157	35,400			133	30,000
East 2	+142	+32,000	157	35,500	+142	+32,000	122	27,600			104	23,400
Intersection A .	+142	+32,000			+142	+32,000			+142	+32,000		
Intersection B .	103	23,200	164	36,900	53.3	12,000	1.8	408	43.3	9,740		
Truss bolts:												
Slot			31.4	7,060			35.8	8,060			5.4	1,220
Muck bay	-2.5	-570	12.5	2,810	8.7	1,960	19.1	4,300		5,170	2.8	660
West	19.9	4,480	23.7	5,330	6.5	1,460	41.7	9,370		6,320	159	35,800
East	36.0	8,100	4.3	960	20.1	4,530	48.3	10,860			63.1	14,200
Center	+142	+32,000	113	25,600	+142	+32,000	104	23,500	+142	+32,000		

+ = Out of range or quit working.

indicates that the yield strength of the rock bolts was not being exceeded.

Figure 15 is an idealized drawing of how the instrumented rock bolts interacted with the cemented backfill in the vein portion of the stope as mining progressed. This interpretation is based on conventional theories of rock bolt reinforcement that state that tensioned rock bolts create a self-supporting compressive arch across the opening (Lang 1961; Hoek and Brown 1980; Stillborg 1986; Brady and Brown 1993). The illustration is also based on visual observations, closure measurements, and load readings on the vertical rock bolts gathered during this project. Initially, in stage 1, there is no wall closure, pressure in the backfill, or load on the reinforcing rock bolts. Then forces in the backfill, created as the bearing plates resist backfill deformation caused by wall closure, form a cone of compression in the backfill (stage 2). The backfill is self-supporting until the backfill breakup progresses to the point where the overlap of the cones of compression between adjacent vertical rock bolts is eliminated (stage 3). The backfill then collapses because of gravity.

BACKFILL TEMPERATURE

The instrumented bolts and two of the earth pressure cells had temperature sensors attached in case large temperature fluctuations required that calculations be made to compensate for these fluctuations. The sensors on the bolts were on the end of the bolt with the strain gauge, and the temperature readings reflected the position of the gauge with respect to the surface of the sandfill. The readings from the 2.4-m- (8-ft-) long rock bolts in the intersection were lower than the other readings because the ends of these bolts were exposed to the air. Figure 16 shows average temperatures for the bolts in the backfill and those in the intersection. The 47.2 °C (117 °F) in-fill temperature at day 2 was the highest temperature recorded in the backfill and stemmed from the heat of hydration of the cemented backfill. The 32.2 °C (90 °F) recorded on the IA, IB, and IC rock bolts was air temperature in the unventilated area above the backfill. The data show that no temperature compensation was required for the strain gauges because loads were significantly higher than the temperature compensation. The data also give an indication of the heat load to the ventilation system from the heat of hydration of the cemented backfill.

TRUSS LOADS

Immediately after installation on day 14 and during mining of cut 9 on the 5660 level, the load cell on the vertical rock bolt in the center of the truss took on loads to 116 kN (26,000 lb), while the load cells on the horizontal leg showed loads from 0.4 to 33.4 kN (100 to 7500 lb) (figure 17). Loads on the horizontal legs remained fairly constant until day 87, at which time cut 1 from the 5750 level was being mined past the instrument locations 6 m (20 ft) below.

On February 15, 1998 (day 122), load on the horizontal legs increased suddenly while load on the vertical leg decreased. Visual inspection on February 18 showed that the backfilled intersection of cut 7 had slumped onto the top of the instrumented backfill. It was noticed that the yoke of the slot leg of the cut 7 truss had come off the horn bracket (figure 18) and supplied no support at all. Then, between 6:00 p.m. on February 28 (day 136) and 6:00 a.m. on March 1, the load cells on the four horizontal legs of the truss showed sudden increases of 6.7, 7.6, 9.3, and 19.1 kN (1500, 1700, 2100 and 4300 lb). The next readings (12 hr later at 6:00 p.m. on March 1) showed that loads on the east and west legs of the truss had increased from 111 and 80 kN (25,000 and 18,000 lb) to 178 and 165 kN (40,000 and 37,000 lb), respectively, while loads on the slot and muck bay legs had dropped from 53 and 49 kN (12,000 and 11,000 lb) to 13.3 and 2.7 kN (3000 and 600 lb), respectively.

Load on the vertical instrumented rock bolt in the truss also showed an increase from 35.6 kN (8000 lb) to the 142-kN (32,000-lb) limit of the vibrating-wire strain gauge on day 12 as cut 9 on the 5660-05 level was mined under the intersection. At approximately the same time, the instrumented rock bolts on the east and west truss leg ends reached loads of 60.9 and 27.7 kN (13,687 and 6236 lb), respectively. These loads then gradually leveled off at 36.5 and 19.6 kN (8200 and 4400 lb).

After day 87, the instrumented rock bolts showed decreases in load on the east and west legs and an increase on the muck bay leg, while the load cells all showed an increase in load. Readings from the rock bolt on the east leg of the truss stopped shortly after, probably as a result of backfill deformation cutting the signal wire.

At day 136, the two remaining instrumented rock bolts on the muck bay leg and the west leg also recorded sudden increases in load similar to, but of a lower magnitude than, those of the load cells at the truss bracket. Readings from the instrumented rock bolt on the west truss leg stopped on day 142 after cut 2 from the 5750 level had mined under. Figure 19 is a graph of data for all three mining cuts.

Data from both the load cells and instrumented bolts indicate that a major redistribution of load was taking place in the intersection during this 18-hr period. Table 4 is a summary of the readings over the 18-hr period for the rock bolt load cells and the instrumented rock bolts. The truss legs along the vein functioned as expected, but the legs extending into the muck bay and slot failed to hold load and were ineffective.

Visual inspection of the intersection on March 3 showed that the backfill in the northwest corner of the intersection had collapsed onto the backfill in cut 9, but that the truss was still above the backfill. It was not possible to determine how far the failure extended along the west side of the stope, but it is thought that, based on instrument response, failure was limited to the first 3 m (10 ft) of the west side. The 3-m- (10-ft-) long cap placed here probably stopped further collapse, but the area was not accessible to confirm this belief. The weight of the backfill from cut 7 on top of the instrumented backfill and continued wall closure from mining in cut 2 on the 5750-05 level caused the intersection to collapse. The collapse was not hazardous to miners because there were two intact backfilled cuts between the collapse and the active mining area.