

Longwall Tailgate Support-Consideration, Design and Experience

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For many coal mines the search for the optimum longwall tailgate support continues. This quest has been intensified in recent years by a number of factors. Scarcity and the resultant increases and projected increases in the price of wood cribbing--the traditional longwall tailgate support--has been one impetus. Longwall tailgate ground control problems that are partially caused by inconsistent wood quality or the "soft" performance characteristics of wood cribs have been other factors which has led to experimentation with differing support types. Manufacturers have also contributed to this impetus by developing new lines of supports with either better performance characteristics or, in some cases, the ability to customize the support performance characteristics in an attempt to more closely match the performance to the conditions in which they will be used. Accident trends associated with material handling, especially in view of an aging work force, along with the costs, inconvenience, and volume of material handling associated with the traditional methods are other strong motivations for many companies to investigate lighter, more compact, and/or novel approaches to providing tailgate support. Yet, all of this must be examined against a requirement that the performance of the secondary tailgate support system must be flawless. Safety and economic demands in today's longwall coalmine environment leave room for little else.

This paper discusses a longwall tailgate standing support design methodology. This design technique, based on actual in-mine measurements of tailgate loading, can be used to determine the appropriate application of alternative roof support systems or to design in-mine trials such that a fair and equitable comparison of different support systems can be made. The methodology uses the performance characteristics generated in the NIOSH Mine Roof Simulator (MRS) to calculate the load density required for various support systems based on the measured ground reaction behavior at a particular mine site and the stiffness characteristics of the supports.

Four different standing support areas in addition to conventional 4-point crib supports were installed in a longwall panel tailgate in a Pittsburgh seam mines and evaluated based on this design methodology. These standing supports were: Heintzmann Corp. Alternative Crib Supports (ACS's); HiTech Corp.'s Pumpable Crib Supports; Strata Product's Propsetters; and Burrell's "The Can." A cribless area, using Jennmar's cable trusses, was also installed in the same panel tailgate.

Tom Barczak

Tom Barczak began his career in mining as Research Physicist at the US Bureau of Mines in 1976. In addition to working for the Bureau of Mines, he has worked for the Dept. Of Energy and is now employed by the National Institute for Occupational Safety and Health (NIOSH) at the Pittsburgh Laboratory. His expertise is primarily in the field of ground control, specializing in the design and evaluation of roof support systems. Tom is the technical manager of the Strategic Structures Testing Laboratory, where research is conducted on full scale testing of emerging roof support technologies.

Thomas P. Mucho

Tom Mucho began his mining career as a laborer at J & L's Vesta #4 mine in 1971. He joined Bethlehem Mines Corporation as a co-op in 1973. While with Bethlehem, Tom Mucho became Superintendent at Marianna #58 mine and later held that same position at Mine #84 for ten years. For five years, beginning in 1991, he was a mining health and safety researcher for the former U. S. Bureau of Mines. More recently Tom was Senior Mine Engineer at Cyprus Emerald, and most recently, was named the Branch Chief of the Disaster Prevention and Response Branch at the Pittsburgh Research Center of NIOSH.

Tom Mucho is a graduate of California University of Pennsylvania, West Virginia University- where he received his mining engineering degree- and most recently has done graduate work in geotechnical engineering at the University of Pittsburgh. Tom Mucho has authored or co-authored some 32 papers on mining, mainly in the areas of coalmine ground control and ventilation.

ABSTRACT

Maintaining ground stability in the gate roads, particularly the tailgate, has always been critical to the success of longwall mining, both in terms of safety and productivity. Several new support technologies have been developed in recent years to replace conventional wood and concrete cribbing for secondary roof support. While the primary goal continues to be better ground control, these new support technologies also help to reduce material handling efforts. As longwall panels increase in length, another important requirement for secondary support is to reduce the restriction of the entry, and again there are advantages to be gained with these new support technologies. This paper examines these new support technologies and provides insights into the requirements for the design and installation of modern longwall tailgate support systems. First, a design methodology is proposed which will optimize the installation of a particular support technology by matching the stiffness and capacity of the support to the tailgate ground reaction behavior. Second, the material handling aspects are analyzed in terms of the terms of the transportation of the support material into the mine and work required to construct a particular support system. Third, the deformation characteristics of the various support structures in addition to the size of the support are evaluated in relation to the restriction imposed by the support on the tailgate travelway. These factors are examined both in a generic sense and through a case study of alternative support technologies at a western Pennsylvania mine site.

INTRODUCTION

Adequate tailgate support is essential for successful longwall mining. Safety considerations, especially the limited escape routes from a longwall face, demand that the tailgate entry be a negotiable travelway. The location of the face electric, support equipment, and belt line in the head gate entries dictate that the tailgate may be the only option for mine workers to escape from the face in the event of an emergency. A recent example is the longwall gob fire which occurred at a mine in Utah this past year (1998) in which several miners evacuated through the tailgate entry to safety. In addition to the emergency travelway requirements, inadequate tailgate support that results in poor ground control and blocked tailgates due to roof falls can severely retard or halt production. The heavy reliance by these mines on the longwall production for survival dictates that loss of this capability for protracted time periods cannot be tolerated. Ventilation is another issue that depends on proper tailgate support. As the panel lengths continue to increase, excessive closure or restriction of the tailgate entry by the deformation and/or density of the standing support can be problematic and potentially unacceptable. In gassy mines, it also may be required that the tailgate be kept open in by the longwall face in order to establish effective bleeder ventilation of the tailgate area. Another important issue to consider is the material handling aspects of tailgate supports. Considering that the workforce is aging, consideration should be given to reducing the material handling effort to prevent injuries to the mine workers. The time requirement to install supports also needs to be minimized as longwall panel lengths and productivity continue to increase. Therefore, the onus is on the mine engineers to install an optimum support system that maintains adequate control of the tailgate ground conditions at all times and with minimal ventilation resistance and material handling considerations.

Historically, the importance of ground control issues has led to very conservative applications of tailgate support, using primarily conventional wood crib structures. When properly designed, conventional wood cribs provide effective ground control in most longwall tailgate entries, and in the past have relatively inexpensive such that mines could afford to use a high density of cribs at relatively little cost. However, increasing timber costs, inconsistent timber quality that led to poor crib performance, and inadequate supplies of timber for western mines have reduced the applicability of conventional wood cribbing, and have encouraged many mines to consider other options for tailgate support.

Today, there are several alternative support technologies that have been developed. These innovative support systems not only provide superior roof support capabilities, but in many cases offer benefits relative to material handling. These material handling advantages allow these supports to be installed in less time with less effort. All of these new support technologies have been safety tested at the NIOSH Safety Structures Testing Laboratory, whereby their performance characteristics have been determined. Since the performance characteristics of these supports are unique, the best practices that have been developed largely through trial and error with conventional wood cribbing may not be applicable for these alternative support technologies. In addition, these new supports have limitations,

which if not properly recognized, can lead to poor support application and inadequate tailgate ground control.

Therefore, with so many options to consider and the importance of achieving proper ground control at minimal cost with minimal installation effort, the trial and error approach to longwall tailgate support can be costly and indecisive. This paper examines the various new support technologies that have been developed in recent years, and provides a design methodology that will allow mine operators to optimize the advantages of these emerging roof support technologies. In addition to helping mine operators optimize tailgate support, this information will provide MSHA with a means to assess various support systems on an equivalent basis when approving roof control plans. A case study of the performance and installation of alternative support technologies at a western Pennsylvania coal mine is examined as part of this study.

SUPPORT TECHNOLOGIES NOW AVAILABLE FOR TAILGATE SUPPORT

Although there have been several trials and successful installations of intrinsic support such as trusses and cable bolts, this paper will focus on standing roof support technologies. Standing supports must be loaded in compression to produce the required capacity to achieve equilibrium of the mine roof. In other words, the roof has to move down before the standing support develops sufficient load carrying capacity to achieve equilibrium of the mine roof and floor. Since it is this very downward movement of the roof that we are trying to control, the most important design parameter for standing supports is the stiffness of the support system. Stiffness is simply a measure of how quickly a support develops its load carrying capability in response to convergence of the mine roof and floor. Stiffer supports develop equivalent load carrying capacity with less displacement than softer support systems.

Another important design parameter is the load carrying stability of the support. More specifically, it is important to know how well the support can sustain its load carrying capability as a function of convergence. Stiff supports, such as the non-yielding concrete supports, which develop load carrying capacity quickly but fail at little convergence are not practical in many longwall tailgate applications. In order to keep such supports from failing prematurely, a large number of supports must be installed, such that the roof loading is sufficiently shared among several supports, while achieving a high enough load density to keep the convergence below the failure point for any one support.

A general discussion of the performance characteristics and key points in the construction of standing roof support technologies is summarized as follows.

Conventional Wood Cribs – Conventional wood crib supports have been the most common form of tailgate support since longwall mining began. They are typically constructed in the form of 4-point or 9-point configurations. The capacity of the crib is determined primarily by the strength of the wood and the contact area. Hence, a wide range of support capacities can be designed into a wood crib support. Ideally, they should be constructed from the same type of wood, or at least wood of similar strength to avoid instability and degradation of support capacity. Overhanging timbers will significantly improve stability and increase capacity by as much as 10 pct. The aspect ratio of the crib should be between 2.5 and 5.0. Timber lengths should increase by 3 inches for each additional foot of crib height, starting with 26 inch length timbers at a 5-ft construction height. Well constructed wood cribs will yield through 20 pct strain (from the original crib height to 80 pct of the original crib height) before shedding load.

Engineered Wood Crib Supports – Strata Products USA has pioneered the development of engineered wood crib supports with the Link-N-Lock and Hercules crib. The Link-N-Lock crib uses notched timbers to improve crib stability by completely interlocking timbers similar to log cabin construction. In addition, the notching provides full timber contact which greatly improves capacity compared to conventional wood cribbing. For example, a 24-inch Link-N-Lock crib develops 93 tons of support capacity at 2 inches of displacement compared to only 42 tons for a 4-point wood crib constructed from mixed hardwood (6x6) inch timbers. The improved stability due to interlocking allows for smaller timber lengths and wide-side-up construction resulting in lighter weight timbers to improve material handling. The Hercules crib combines end-grain timber load with cross-grain timber loading to combine the characteristics of a wood post (high stiffness) and a conventional wood crib (large yield) into a single support. It can be constructed in a variety of configurations to provide a wide range of support capacity and stiffness.

Capacities range from around 100 tons for HM-4 designs to over 800 tons for HM-18 designs. American Commercial Inc is currently developing the Tri-Log Crib, which is similar to the Strata Products Link-N-Lock crib except that a triangular configuration is constructed. The Tri-Log Crib also offers the advantages of smaller and lighter timbers and higher capacity afforded by the interlocking timber construction.

Conventional and Engineered Timber Post Supports – Conventional timber posts will fail at less than 1 inch of convergence. Header boards or crib blocks will improve the yield capability of timber posts. Improvement in displacement will be approximately one half of the total thickness of the header boards or crib blocks. An 8-inch diameter hardwood post will provide about twice the capacity of a 4-point wood crib constructed from mixed hardwood or poplar timbers. The Propsetter Support developed by Strata Products USA improves the yield capability of a timber post to 8 -10 inches of displacement, while providing support capacity comparable to a mixed hardwood, 4-point wood crib. The deformation is controlled in the engineered bottom area of the Propsetter Support. The load is controlled to eliminate buckling, which is the common failure mode in conventional timber posts. American Commercial Inc. is also developing a yieldable timber post which is currently undergoing performance testing at NIOSH.

Non-yielding Concrete Supports – The conventional concrete supports include donut-shaped, stacked-block, and solid-shaped structures made from high strength concrete which is often reinforced with small steel fibers. These non-yieldable concrete cribs are very stiff supports which fail at less than 1 inch of convergence with no useful post-failure residual strength. As such, they are not well suited to areas of high deformation such as longwall tailgates. The yield capability of concrete cribs can be improved by adding wood. The improvement in displacement will be about one half the thickness of wood used in the crib construction. Whenever wood is added to a concrete crib construction, the initial behavior of the crib will resemble that of a wood crib not a concrete crib. The wood crib behavior will continue until the wood is compressed to nearly half of its original thickness. Concrete has 8 to 10 times the compressive strength of wood, but unlike wood does not obtain the full compressive strength of the material in crib structures. When designing concrete cribs, the compressive strength of the concrete material should be reduced by a factor of 2 to determine the expected capacity of the concrete crib.

Deformable Concrete Supports – Several deformable concrete support systems are now available that are specifically designed for use in longwall tailgates. These include: (1) The Can Support developed by Burrell Mining Products, (2) the Pumpable Crib developed by Heintzmann Corporation, and (3) the Tekprop developed by FOSROC. All three utilize the same basic concept which is exterior confinement to a column of relatively weak concrete or cementitious grout material.

The Can Support utilizes a steel container with air-entrained concrete inside. The Can is prefilled as part of the manufacturing process and is shipped as a complete unit. Due to their size and weight, they are installed by a machine-mounted, hydraulically-activated claw arm. The Can must also be topped off with timbers to provide roof contact, which can be critical to the performance of the support. The capacity (combined strength) of the timber must exceed the strength of The Can to transfer load into the Can, otherwise initial behavior will be that of a wood crib instead of The Can. This will typically require timber contact over the full top surface of The Can. The Can is a very stable support capable of yielding through 50 pct strain as the steel container folds like an accordion to provide continued confinement to the air-entrained concrete, which crushes to a powder during the load application. Load capacities are controlled primarily by the top surface area, ranging from 60 to 200 tons for 18 to 36-inch diameter Cans.

The Heintzmann Pumpable Crib utilizes a high tensile-strength-textile bag as a form into which a cementitious grout is pumped in place in the mine entry. The bag also acts to provide confinement during load application to the pumpable grout, which is more dense and brittle than the air-entrained material used in Burrell Can Support. The bag expands during loading, but provides enough confinement to keep the fractured concrete column intact and provide sufficient post failure strength (comparable to a 24-inch diameter Can Support) to carry the roof load.

The FOSROC Tekprop acts essentially as a hydraulic cylinder where a cementitious grout is pumped into a thin-walled metal container causing the piston section to expand outward until roof contact is achieved. The metal container acts primarily as a form and does not provide sufficient confinement to prevent buckling or shear failure of the prop.

Yielding Steel Supports – There are several friction type secondary support systems that have been developed through the years and some of these continue to be used as supplemental support. Recently, Heintzmann Corporation developed the Alternative Crib Support (ACS), which is the first relatively widely used yieldable steel support for longwall tailgate applications. The ACS is essentially a steel pipe section with a threaded end for height adjustment, combined with a variety of end pieces to provide yield capability to the support. The end sections are designed with a: (1) flat steel plate, (2) pizza pan steel plate, and (3) steel plate with wood timbers to provide progressively greater yield capability. Other emerging yieldable steel supports currently under development include the Rock Prop by Strata Products and the Stretch Prop by Ferrocraft Inc. The Rock Prop is pumped full of water to cause extension of the prop to the mine roof. Once the prop is pressurized against the mine roof, a collar is locked in place transforming it into a friction-type prop where the piston is forced into the smaller annulus of the prop body. The Stretch Prop is pumped full of cementitious grout to active extend and load the prop against the mine roof. Once cured, the cementitious grout then provides load carrying capacity, and the steel container provides confinement to allow yielding of the prop while the cementitious grout is fractured and deformed.

MATCHING THE SUPPORT PERFORMANCE TO THE GROUND BEHAVIOR

Obviously, the support system is employed to prevent roof falls. How this is accomplished is the important issue. While secondary supports provide the last means of support in the event there is roof failure above the bolted horizon, the primary function of the secondary support system is to assist the primary support system in maintaining the integrity of the immediate roof. As the ground deforms by the creation of an opening due to mining, it gradually sheds load to the surrounding mine structures, which in the case of longwall mining are the gate road pillars and longwall panel. Secondary support must be placed in sufficient time and develop sufficient capacity to bring deformation of the ground into equilibrium before a critical deformation is reached at which point failure of the ground is inevitable. Otherwise, the secondary support will be required to carry the entire dead weight of the detached rock mass to prevent a roof fall from occurring. This embodies a fundamental concept in rock mechanics known as the "ground reaction curve"(1).

In longwall mining, the tailgate entry is subjected to three phases of loading and equilibrium. Each will have a distinct ground reaction curve. The first phase occurs on development where the mine opening is created and the primary support (roof bolts) are installed. Relatively little ground movement occurs during this phase since the development loads are small and the primary support is sufficient to provide equilibrium. The next phase is adjacent panel mining. The future tailgate is subjected to side abutment loading, and while secondary support is typically installed to ensure that equilibrium of the rock mass is obtained, the convergence is typically minimized by the load density of the support. The final phase of tailgate behavior is where the active tailgate is subjected to front abutment loading from the panel extraction. It is this phase where the secondary supports play their most important role in preserving the stability of the entry. A hypothetical tailgate ground reaction curve is shown in figure 1. It should be noted that the ground reaction curve will be a function of the several factors in addition to the load density of the support system. These include the geology, roof spans, vertical as well as horizontal stress around the opening, and some time dependent factors such as creep. Hence, the ground reaction curve is generally unique to a specific mine and can change within the mine as these factors change. From the perspective of secondary support design, it is important that the ground reaction curve be examined under the worst case load conditions where ground control is required. Since the ground reaction is dependent upon roof span, a different ground reaction behavior will typically be observed in intersections compared to the non-intersection areas of the entry. Hence, the support design must be altered for the intersections to accommodate this difference in ground reaction.

It is seen from the hypothetical tailgate ground reaction curve (figure 1) that if the goal is to prevent convergence completely, then the full abutment load must be resisted by the primary and secondary support system. This resistance for all practical purposes cannot be obtained by the installation of secondary support since the required capacity would need to be equivalent to that of all the coal that was removed by the mining process. The support capacity required to achieve equilibrium is reduced as the deformation increases, since the roof is shedding load to other mine structures as it deforms. In other words, by allowing the roof to deform and shed some load to the coal pillars and longwall panel, less support capacity is required since the roof load is decreased. Hence, the lowest required support capacity would be one that is developed just before the critical roof deformation occurs where failure of

the immediate roof is fast approaching. However, designing to this lower limit of support capacity leaves no margin of error in the event that load conditions worsen. Also, it can be seen that if a support system is too soft (develops load carrying capacity too slowly), equilibrium of the mine roof will never be achieved and failure of the roof will be inevitable.

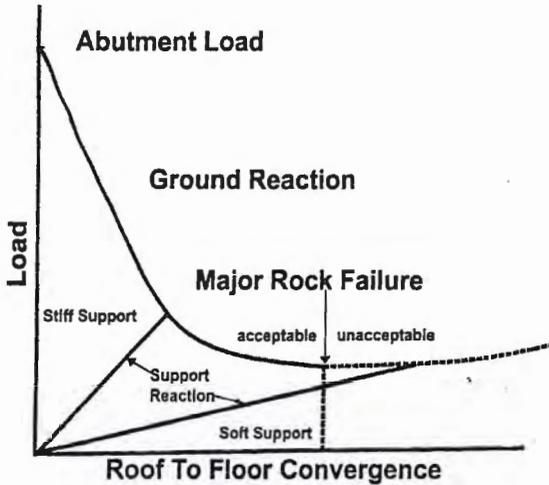


Figure 1. Ground reaction curve concept.

Since most standing supports are passive supports, convergence must take place before sufficient support loads are developed to provide equilibrium. The amount of convergence required to produce equilibrium is then a function of the stiffness of the support system. Equilibrium will be achieved at less displacement for a stiffer support system since the support resistance to roof loading will develop quicker (at less displacement) compared to a softer support system. Hence, as the support load resistance (load density) of a support system increases, the convergence at which equilibrium is attained will decrease. If too much convergence is permitted to occur by utilizing too soft of a support system, failure of the rock mass (mine roof) will be inevitable. Hence, the goal of support design is to provide sufficient support stiffness to ensure that the required support capacity to achieve equilibrium of the rock mass occurs before the rock mass deforms to the point of failure. However, a prudent mine engineer would ensure that sufficient support capacity is developed long before the critical convergence is reached. Since minimizing convergence is achieved by increasing the support capacity (load density) and generally the cost of support, the goal of optimizing the support selection is not to install more support than is necessary to provide a reasonable margin of safety to prevent roof failure.

Design Methodology For Longwall Tailgates

The first step in the design process is to determine the ground reaction behavior. This can be done by installing at least two, and preferably three, support systems of *varying* support system stiffness, and measuring their loading and corresponding convergence of the mine roof and floor. It is important that these supports cover a wide range of stiffness to provide a *full picture* of the ground reaction behavior. As part of this process, an effort should also be made to determine the critical roof-to-floor convergence where roof failure occurs, since this will be a critical design value for the support design. However, in order to do this, a low density support system must be installed that will allow considerable convergence to occur. Since this poses a risk of inadequate ground control, precautions should be taken. One possibility is to set additional wood cribs through this trial zone with the top layer removed such that they could be reinstalled to provide additional support if necessary, or in the worst case provide ground support after the roof deforms (5-6 inches) to the cribs if they cannot be topped off.

Altering the support system stiffness can be done several ways. One way is to utilize the same support and same spacing down the entry, but increase the number of rows of support across the mine entry from one to two to three, which would proportionally increase the system stiffness by the same factors. Another way is to keep the spacing and number of rows of support constant, but use supports of varying stiffness. This will eliminate the impact of both span and roof coverage issues, which can be limiting factors in the support placement (load deformation) strategies. For example, using conventional wood cribs, the support construction could be varied from a 4-point to a 9-point to a 16-point crib. The support load density would increase in direct proportion to the increase in support stiffness. Adjusting the support spacing down the entry can also be considered in that the support load density per unit area of support is proportionally increased as the spacing is decreased, but care should be taken to avoid excessive spacing that will cause span related problems that are independent of the support loading characteristics. A good rule of thumb is that the support spacing should not exceed half the entry width. The load bearing area of the support is also an important factor to consider. The pressure exerted by any support should not exceed the strength of the mine roof or floor.

Measurements of support of loading as a function of displacement (convergence) for the various instrumented supports should be made under the most severe load conditions where ground control is required. The load-displacement data is then used to generate a plot of support load density as a function of convergence (ground reaction curve). Each support type with different stiffness represents one data point on the ground reaction curve. The support load density is determined as the measured load in the support at the observed convergence times the number of supports per unit area of mine entry (equation 5). A convenient approach to defining a unit area is to examine a section of entry equal to the entry width, then the unit area is simply the entry width squared. For a single row of supports employed on a constant center-to-center spacing, the support load density can be determined by equation 6.

$$\text{Support Load Density} = \frac{\text{Number Supports} \times \text{Support Load}}{\text{Area Of Support Coverage}} \quad (1)$$

$$\text{Support Load Density} = \frac{\text{Support Load}}{\text{Center - To - Center Spacing} \times \text{Entry Width}} \quad (2)$$

Once the ground reaction curve is developed, the center-to-center spacing (down the mine entry) of alternative support systems employed in a single row arrangement required to achieve ground control (equilibrium) at a desired convergence can be determined from equation 3. The center-to-center spacing of a double row of supports is simply twice that of a single row arrangement.
 where Spacing(displacement) = Center-to-center spacing in feet of a single row of supports;

$$\text{Spacing (displacement)} = \frac{\text{Capacity (displacement)}}{\text{Load Density} \times \text{Entry Width}} \quad (3)$$

Capacity (displacement) = Individual support capacity in tons at a specified displacement (obtained from laboratory performance data) equal to the desired convergence control;
 Support load density = Support load density in tons per sq. ft. at the required convergence (obtained from ground reaction curve);
 Entry Width = Width of the entry in feet.

This design methodology is a valuable tool in optimizing the utilization of standing secondary roof support technology. However, as previously described it is still up to the mining engineer to decide how close to the critical convergence he/she wants to operate based on their knowledge of the particular ground conditions. A margin of safety is provided by designing for a convergence that is less than the critical convergence (minimal acceptable support load density). In order to make equivalent comparisons of alternative support systems, a safety factor can be quantified by comparing the design support load density to the minimal acceptable support load density which will be representative of the maximum

allowable (critical) convergence. This is referred to as the ground reaction curve (GRC) safety factor (equation 4).

$$\text{GRC Safety Factor} = \frac{\text{Design Load Density}}{\text{Minimal Acceptable Load Density}} \quad (4)$$

Another factor to consider is whether the support is being fully loaded and how much reserve capacity is left in the support at the design load. In the event that load conditions worsen beyond expectations, this reserve support capacity may be needed to support the mine roof. If the support characteristic is such that the support sheds load quickly after reaching its peak load, such as the non-yielding concrete supports, then consideration must be given to avoid designing near the peak loading capability of the support. A safety factor for the support can be defined based on the support loading at the required support load density in relation to the peak loading capability of the support (equation 5). Hence a safety factor of 1 indicates that there is no reserve capacity available and a safety factor of 2 indicates that the support is loaded to only 50 pct of its maximum support capacity.

$$\text{Safety Factor (Support)} = \frac{\text{Peak Load Capability}}{\text{Load at Installed Load Density}} \quad (5)$$

MATERIAL HANDLING ISSUES SHOULD BE CONSIDERED IN THE SUPPORT SELECTION

Studies indicate that over 55 pct of the permanent disabling injuries in underground coal mining are due to material handling. An even greater number of non-disabling injuries may be linked to material handling in mining. It is likely that these accident trends will continue and perhaps grow worse due to an aging workforce. The construction of secondary support systems has historically required repetitive lifting of large volumes of bulky support materials. Coupled with the poor conditions where space and maneuverability is limited, and the fact that many of the support materials exceed 40 lbs in weight, this activity is responsible for numerous injuries to the mine workers. Such activity has been classified by the National Occupational Health Survey of Mining as a heavy lifting risk factor, exposing miners conducting this activity to a high risk for musculoskeletal repetitive trauma disorders. It is also very likely that future younger, but inexperienced, miners will also endure a high incidence rate of these kind of accidents until they become more experienced. Hence, material handling should also be a primary consideration in the application of longwall tailgate support technologies.

The first issue regarding material handling is getting the material into the mine. Tailgate support materials are typically loaded onto either supply cars or shield carriers and transported into the mine by a rail haulage system. A typical supply car will be 7 ft wide and 20-24 ft in length with a 19-21 inch bed height above the track rail. The shield cars are smaller, 14-16 feet in length, but are 8-12 inches lower with more clearance to the mine roof, hence a higher stack of material can be transported on them. At the longwall entry, the supports are typically unloaded by a battery powered fork lift, a battery powered bucket scoop, or a battery powered shield hauler. How the supports are packaged can be critical to the overall material handling requirements. Generally the goal is to bundle the supports in full support increments. This will minimize the construction effort by placing the correct amount of material in the vicinity where the support is to be constructed. Table 1 documents the relevant parameters associated with transportation of support material into the mine.

Examining table 1, it is seen that three support systems provide significant transportation advantages in terms of the volume of support material compared to conventional 4-point wood cribbing. These are: (1) Propsetter Support - Strata Products USA, (2) Pumpable Crib - Heintzmann Corporation, and (3) ACS - Heintzmann Corporation. Over three times as many Propsetter Supports can be transported on a typical supply car compared to conventional 4-point wood cribbing. Likewise, four times as many ACS's can be transported. The Pumpable Crib requires that only the collapsed bag be brought into the mine, since the cementitious grout is typically pumped from a surface installation through a borehole. As a result, 100 bags (five times the number of 4-point wood crib supports) can be transported easily into the mine on a single rail car. The 24- and 27-inch Link-N-Lock cribs are comparable to 4-point wood cribs while the 36-inch Link-N-Lock crib is comparable to a 9-point wood cribs in terms of material

transportation requirements. Also, concrete cribs constructed two blocks per layer from ventilation stopping blocks have similar material transportation requirements as that of conventional 4-point wood cribbing. The Can support is the bulkiest of all supports. About half as many Can supports can be transported on a single supply car as timber for conventional 4-point wood crib construction. The steel-fiber-reinforced donut and solid-shaped concrete cribbing require the most cars to transport an equivalent number of supports into the mine relative to conventional wood cribbing.

Table 1. Relevant material handling parameters for transportation of support material into the mine (normalized to 6 ft mining height).

Support System	Pieces per Support	Material volume per support ft ³	Transport volume per support ft ³	Number supports per supply car
4-Point cribs ¹	24	15.0	15.0	20
9-Point cribs ¹	36	22.5	22.5	13
24-inch Link-N-Lock	48	11.7	14.0	21
27-inch Link-N-Lock	48	13.4	15.7	21
36-inch Link-N-Lock	48	18.7	21.0	14
Propsetter (8.5 in dia)	3	3.8	5.3	64
Stopping block cribs	24	10.7	10.7	18
SFR Donut Cribs	24	11.1	20.1	8
SFR Solid Blk Cribs 4x8x24 in (576 in ²)	54	24.0	24.0	7
Heintzmann Pumpable Crib ²	1	1.2	1.6	103
Burrell Can (24 in dia)	4	18.8	24.0	11
Heintzmann ACS (100 ton)	2	0.8	4.2	80
Hercules HM-9(30)	18	22.5	30.0	9
30-inch Tri-Log	36	12.4	15.0	28
36-inch Tri-Log	36	15.4	18.0	18

¹Based on 6x6x30 in poplar or mixed hardwood timbers

²Material assessment considers only that used underground, i.e. the bags for forming the support. It does not include the hardware required to support the bags for filling, since this hardware is used over and over again. Since the supports were pumped from the surface, the grout material is not included in this assessment.

The next issue pertains to the construction of the supports. The primary factor to consider is the labor involved in the support construction and the rate of installation of the support structures. From an injury perspective, the size, weight, and number of pieces handled per unit time are relevant factors. Ideally, the energy required to construct the support would be used to define the risk assessment for musculoskeletal injuries. However, an energy analysis that considers the physiological demand on the human body is quite complex and is beyond the scope of this paper. In lieu of this complex analysis, a computation of work (weight of piece times the lifting height) can be examined. The efficiency of the support construction can be judged in terms of the installation rate and the construction effort (work) per ton of support capability. Table 2 shows the relevant parameters for support construction.

Examining table 2, it is seen that the construction effort increases dramatically for supports that require piece-meal construction using large numbers of heavy pieces such as conventional concrete cribbing. The work required to construct a steel-fiber-reinforced donut concrete crib is twice that of a conventional 4-point wood crib. As a result, the installation rate for these supports can be as low as 6 - 10 supports per shift compared to an average of fifteen supports for 4-point wood cribs. A good example of the benefits provided by these new support technologies is revealed by comparing a 24-inch Link-N-Lock crib to a conventional 4-point wood crib. Both require about the same work to install, but when

normalized to the support capacity, the 4-point crib requires 3.2 times the work per ton of support than that of the 24-inch Link-N-Lock crib. Minimal effort is required for the construction of the Propsetter (535 ft-lbs), the ACS (636 ft-lbs), the Burrell Can (504 ft-lbs). Average installation rates with the Propsetter and the ACS are about twice that of conventional wood cribbing. The installation rate with The Can support depends on the logistics of the unloading and installation activities which require machinery to accomplish. The installation rates are estimated to vary between 20 and 30 per shift in a 6-8 ft seam height. The Pumpable Crib which is poured in place currently requires manual labor to lift the 55 lb grout bags from a pallet positioned on a forklift near the pump. Heintzmann Corporation is planning on developing a batch system for the grout pumping activity, which will all but eliminate the material handling efforts for this support, with the exception of installing the forms to hold the bag during pumping and dismantling them afterwards. With a three-person pumping crew underground and 4 people handling material at the pump station aboveground, 45 Pumpable Cribs per shift have consistently been installed in a test section at a western Pennsylvania mine site.

Table 2. Assessment of support construction parameters for various support technologies.

Support System	Number Pieces per Support ¹	Weight per Piece, lbs	Labor required man-hrs/shift	Const. rate ² , supports per shift	Const Work ³ , ft-lbs	Work per ton of support ⁴ , ft-lbs/ton
4-Point cribs ⁵	24	29	16	15	2,262	84
9-Point cribs ⁵	36	29	16	10	3,393	38
24-inch Link-N-Lock	48	16	16	13	2,400	26
27-inch Link-N-Lock	48	18	16	12	2,700	26
36-inch Link-N-Lock	48	28	16	10	3,900	30
Propsetter (8.5 in)	3	31/11/16	16	30	535	13
Stopping block cribs	24	48	16	15	3,744	N/A
SFR Donut Cribs	24	61	16	10	4,575	N/A
SFR Solid Block Cribs(576 sq in area)	64	58	16	6	9,907	N/A
Heintzmann Pumpable Crib	1	N/A		45	880 ⁶	23
Burrell Can (24 in)	4	Wood - 28	24	20-30	504	7
Heintzmann ACS (100 ton)	2	Prop - 132 Pizza - 40	24	30	636	6
Hercules HM-9(30)	18	44	16		2,505	35
30 inch Tri-Log	36	17	16	16	1,708	16
36 inch Tri-Log	36	21	16	12	2,357	21

¹Numbers are based on a 6-ft construction height.

²Construction rate is based on case work history at a western Pennsylvania mine site where several of these support systems have been installed. The construction rate is sensitive to the mine conditions as well as the workforce age, experience, and work habits. As such these rates are not absolute. Construction rates at other mines may be higher or lower, but the relative differences among support types should be proportional to those rates shown here.

³Construction work is the cumulative sum of the weight of the piece times the lifting height required to install the piece on the support structure. It assumes that the material is located in the immediate vicinity of where the support is to be installed. It **does not** consider the effort required to carry the material to the area where the support is to be installed.

⁴Based on support capacity at 2 inches of displacement.

⁵Based on 6x6x30 in poplar or mixed hardwood timbers.

⁶Based on manual lifting of 55 lb grout bags from pallet located near pump height into pump hopper during initial installation of this new support technology. It is planned that future installations will utilize a batch operation of the grout compounds to eliminate most of this material handling effort.

PROVIDING A USEABLE ESCAPEWAY IS ESSENTIAL

In addition to material handling, ventilation and travel issues need to be considered. As longwall faces extend in length, it becomes more difficult to provide essential ventilation to the longwall face. Large support structures, particularly when more than one row of supports are utilized, can cause significant interference with the use of the tailgate as a ventilation air course. One way to evaluate the various support systems is to simply consider the cross sectional dimension of the support structure, which are documented in table 3 for the emerging roof support technologies that are now on the market. A more in depth assessment would examine the geometry of the support as well, but that is beyond the scope of this paper.

Table 3. Support factors that may influence the travel way - air way

Support System	Cross-sectional dimension (width), in	Failure tendency to further restrict travelway
4-Point cribs ³	30	High
9-Point cribs ⁴	30	High
24-inch Link-N-Lock	24	Moderate
27-inch Link-N-Lock	27	Moderate
36-inch Link-N-Lock	36	Moderate
Propsetter (8.5 in dia)	8.5	Low
Stopping block cribs	16	Low
SFR Donut Cribs	22	Low
SFR Solid Block Cribs(576 sq in area)	24	Low
Heintzmann Pumpable Crib	30	Moderate
Burrell Can (24 in dia)	24	Low
Heintzmann ACS (100 ton)	4-1/2	Moderate
Hercules HM-9(30)	30	Moderate

This same analysis of cross sectional dimension can also be useful in assessing another important criteria, that being the travelway issue. Obviously, larger support structures reduce the space available for escape, and the application of prop type supports can dramatically increase the travelway in longwall tailgates. For example, figure 2 illustrates the improved tailgate travelway afforded by the application of the Propsetter support. The escapeway issue should also consider the deformation behavior of the support structure. Supports which buckle, such as conventional wood cribs, can severely reduce the travel way of longwall tailgate entries in high deformation environments (figure 3). In comparison to conventional wood cribs, the interlocking of timbers in the Link -N-Lock cribs prevents buckling of these structures to a large degree (figure 4). It is expected that the Tri-Log crib would provide similar advantages. As a result, the application of these engineered timber supports will provide a more accessible tailgate travelway in areas of moderate to high convergence.



Figure 2 - Improved travelway provided by Propsetter Support.



Figure 3 - Restriction of travelway in longwall tailgate supported by double row of 9-point wood cribs.



Figure 4 - Link-N-Lock cribs crush down with little buckling resulting in less restriction to the travelway.

CASE STUDY OF ALTERNATIVE TAILGATE SUPPORTS AT A WESTERN PENNSYLVANIA MINE

Measurement of the ground reaction curve at the western Pennsylvania coal mine indicated that at this mine operating in the Pittsburgh coal seam, the support capacity had a significant impact on the ground behavior in the longwall tailgate (figure 5). The ground reaction behavior was measured 50-100 feet in by the face because it was necessary to maintain the active tailgate in by to the first open cross cut in order to establish ventilation back to the bleeder system. Increasing the support load density by a factor of 2 from 0.625 tons per square foot to 1.25 tons per square foot decreased the convergence in the entry from 4 inches to 1 inch. Conventional 4 point wood cribs installed in a double row with an 8 ft center-to-center spacing in a staggered arrangement (4 ft center-to-center spacing among adjacent rows) resulted in marginal ground control, allowing 4 inches of convergence to occur. Concrete cribs

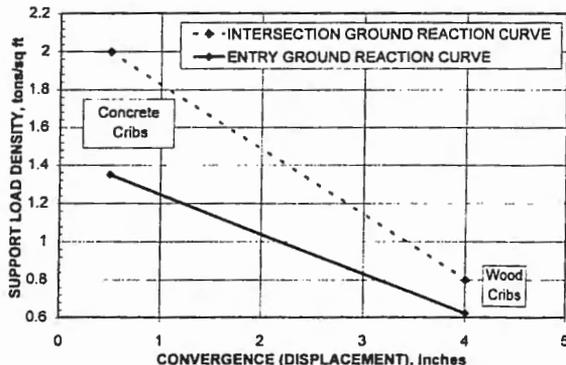


Figure 5. Measured ground reaction curve for western Pennsylvania coal mine.

constructed from concrete stopping blocks reduced convergence to 0.5 inches, but some failed at this deformation resulting in localized poor ground control due to the support failure.

Four alternative standing support technologies were installed at the western Pennsylvania mine: (1) The Can Support (Burrell Mining Products), (2) the Alternative Crib Support (Heintzmann Corporation), (3) Pumpable concrete support (HeiTech Corporation), and (4) the Propsetter (Strata Products USA). These alternative support technologies were installed at a support load density ranging from 1.12 tons per square foot to 1.35 tons per square foot, providing ground control safety factors of 1.79 to 2.16 (table 4). Ground conditions for all these support applications were generally very good, which is consistent with the measured ground reaction behavior and installed support density.

Table 4. Assessment of standing alternative support technologies utilized in study at a W. PA. mine.

Support System	Installed Spacing, ft	Installed Load Density tons/ft ²	Conv. control inches	Safety Factors		Observed Roof Condition	
				GRC ¹	Support ²	Outby face	Inby face
4-Point Wood Crib	8 ft (DR ³)	0.625	4.0	1.00	1.8	Good	Marginal
Concrete Stopping Block Crib	3 ft (DR)	1.35	0.5	2.16 (0 ⁴)	1.0	Good	Marginal
Heintzmann ACS	5.0 (DR)	1.20	1.24	1.92	2.5	Excellent	Good
HeiTech Pumpable Concrete Crib	9.2 (SR)	1.35	0.5	2.16	1.3	Excellent	Excellent
Strata Products Propsetter	4.0 (DR)	1.12	1.6	1.79	1.7	Excellent	Good
Burrell Mining Products Can Support	7.0 (DR)	1.19	1.25	1.90	1.8	Excellent	Excellent

¹Ground Reaction Curve safety factor is determined from equation 4 as the ratio of the installed support load density to the minimum allowable support load density.

²Support safety factor is determined from equation 5 as the ratio of the peak loading capability of the support to the load developed at the installed spacing.

³DR stands for double row of cribs. All double rows of supports were installed in a staggered fashion. The spacing here refers to the spacing of one row of supports. With the staggered arrangement, the spacing between adjacent supports of both rows is half of that of the individual row. SR refers to a single row arrangement.

⁴The roof condition was good prior to the failure of the support. Hence, the installed support load density actually dropped to zero once the support failed and accounted for the deterioration in the integrity of the roof.

Performance Assessment of the Alternative Support Systems

The Heintzmann Corporation Pumpable Crib had the highest load density at 1.35 tons per square foot which limited convergence to approximately 0.5 inches. Conditions both inby and outby the face as shown in figure 6 were excellent with the Heitech pumpable support system. However, it should be noted that the Heitech support also had the lowest support safety factor (1.3) of the four alternative support systems utilized, meaning that load development approached the peak loading capability of the support. If the maximum loading capability of the support was exceeded due to unexpected additional roof loading or variability in the peak strength of the support, the convergence would increase to approximately 4 inches at the installed spacing based on the residual support capacity of approximately 90 tons. Since this is the critical convergence for this mine at which point roof conditions deteriorate significantly, it is critical that the peak pumpable support capacity not be exceeded through the zone where it is desired to maintain full roof control, which means that the spacing must be properly maintained during installation so as not to overload the support into its post failure loading regime.

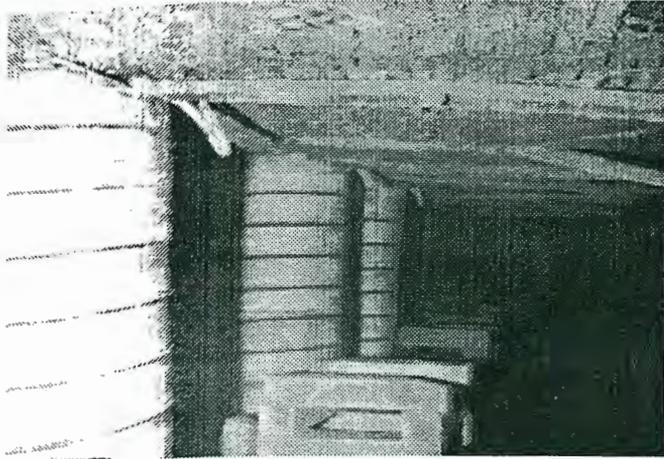


Figure 6a. Outby area supported with pumpable crib.



Figure 6b. Inby area supported by pumpable crib.

The Propsetter support had the lowest margin of safety at 1.79, but even this system was conservatively applied in that the convergence was limited to 1.6 inches. Conditions outby the face were excellent as shown in figure 7a and relatively good inby the face (figure 7b). Some of the Propsetter supports well inby the face mostly in the intersection areas (figure 7c), appeared to be in a state of post-yield deformation where "brushing" (yielding) caused the props to tilt from a vertical orientation, which is normal for this load condition. It does not mean that the prop is shedding load. Another possibility is that the props were being dislodged or moved laterally by flushing of the gob material, floor heave, and/or lateral displacements of the roof relative to the floor by the cantilevered roof beam. Despite these occasional abnormalities in the support condition, the Propsetter was able to maintain an effective air way beyond the first open cross cut inby the face.



Figure 7a. Outby area supported by Propsetter support.



Figure 7b. Inby area supported by Propsetter support.



Figure 7c. First open cross cut intersection inby the face supported with Propsetter supports.

The Heintzmann ACS support had the most limited yield capability of the four alternative support technologies used at this mine. The ACS also sheds load rather quickly after reaching its peak loading capability at about 2.2 inches. However, the installed spacing provided the highest support safety factor (2.5), meaning the loads were kept well below the peak capacity of the support. Likewise the installed load density limited the convergence to 1.2 inches, which is considerably less than the yield point of 2.2 inches. Hence, this is a good example of how a stiff support with limited yield capability can provide effective ground control in a longwall tailgate, provided that a sufficient number of supports are installed per unit area to establish a high enough load density to minimize the ground movement. Figure 8 shows the condition of the entry both outby and inby the face in the area supported by ACS's. Similar to the Propsetter support, a few of the ACS props were tilted inby the face, but continued to provide support capability in this condition without becoming unstable.

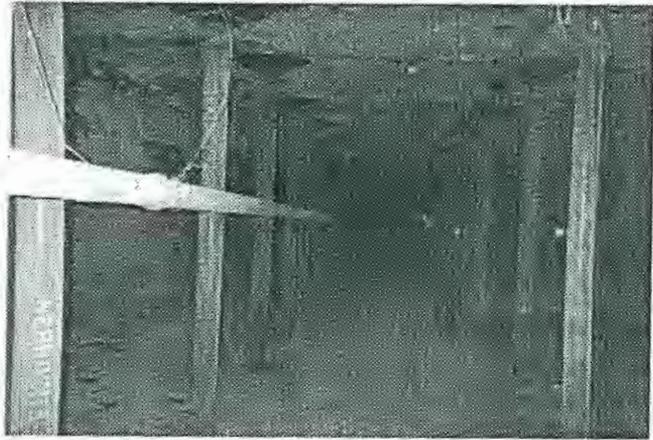


Figure 8a. Outby area supported by ACS supports.

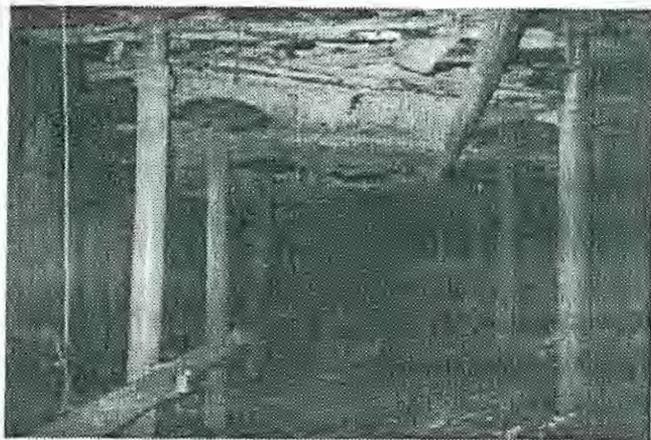


Figure 8b. Inby area supported by ACS supports.

The Burrell Can support installation had a GRC safety factor (1.92) almost identical to that of the Heitzmann ACS supported area. The 1.92 GRC safety factor means that the installed load density is almost twice that needed to prevent roof failures from occurring. The entry conditions, both inby and outby the face were excellent with the Can support as shown in figure 9. Inby, the conditions were slightly better than in the ACS area. This improvement is attributed to the larger surface coverage and improved stability of the Can support compared to the ACS.



Figure 9a. Outby area supported by the Can support.



Figure 9b. Inby area supported by the Can support.

Installation Assessment

Conventional Wood Cribs

A double row of conventional four-point wood cribs on an 8 ft spacing was utilized prior to the installation of the alternative support technologies. Pallets of crib timbers were delivered to the longwall on supply cars. Eight pallets were hauled on each car, which was enough cribs to support approximately 70 ft (21 m) of entry. The pallets of timbers were unloaded and stored between 700 and 1,300 ft (213 to 396 m) outby the longwall face. This distance was required to maintain a roadway around the track-mounted power train in the three-entry gate road. Two pallets of cribs (66 timbers per pallet) per trip were hauled from the storage area to the installation area by a forklift equipped battery powered tractor. A two-man crew installed an average of fifteen cribs per shift. This process was somewhat limited by the sequential order of supply, deliver, and build, as well as the lack of storage space at the installation area.

Heintzmann Corporation's Alternative Crib Supports (ACS's)

The ACS's were delivered to the longwall on supply cars. Each supply car carried 40 ACS's, enough to support 100 ft (30 m) of entry. The ACS's afforded some flexibility over conventional wood cribbing in that they could be stored outby the face or delivered and placed along the rib of the entry for installations at a later date. Three men were used to install the ACS's with an average rate of 25-30 per shift. One problem was encountered with the limited range of adjustment in the ACS's. After seam height measurements were taken and the ACS's were ordered, the floor in the test area hooved. This caused the ACS's to be too long, and floor material had to be removed to install the ACS's. In high areas, the ACS's were installed on up to 12 inches (0.3 m) of crib timbers.

Heitech Corporation's Pumpable Crib Supports

The pumping station was installed approximately 800 ft outby the longwall face in the track entry. Two 1.25 inch polyethylene lines were run from the pumping station to the installation area. Palletized bags of cement were unloaded by the fork scoop and placed at the pumping station as needed. The pumpable crib bags were suspended from the mine roof and stabilized by roof jacks and/or Heintzmann ACS's. The pumping process was somewhat labor intensive requiring 5 men per shift. An average of 8 cribs per shift were pumped. Items addressed during the pumping process included adjusting the water/cement ratio to account for dust suppressant in the water and modification of the stabilizing supports. Since the initial trial, 1300 of these supports have been installed from a surface installation 800 ft (244m) above the mine. Support installation time was greatly increased with peaks of 49 supports installed in an 8 hour shift.

Strata Product's Propsetter Supports

The Propsetter Supports were bundled in groups of six with wedges, headboards, and base plates for transportation into the mine. Twenty four units were transported per supply car, enough for approximately 48 ft (15 m) of entry support. The Propsetters, like the Heintzmann ACS's provided the flexibility of being stored outby or delivered and placed along the rib for installation at a later date. They were cut to length using a hydraulic chain saw powered from the fork scoop and were installed by two men at an average rate of 30 per shift.

Burrell Mining Products "The Can" support

The cans, stacked perpendicular to the track, were delivered to the longwall on shield carriers with 18 cans per carrier. This equates to 63 ft (19.2 m) of entry support per carrier. In order to install the cans, the fork scoop was equipped with a clamp that was capable of grasping the cans and rotating them through 180° to a vertical position and setting them in place. The test area was near the mouth of the longwall panel and had been developed with four entries. This allowed the cans to be stored approximately 300 ft (91 m) from the area to be supported and greatly improved the efficiency of the installation. Three men were able to unload, deliver, and install 20 cans per shift through the test area. In addition to the fork scoop, equipped with the clamp, a bucket scoop and a shield hauler were also

available for delivery of the cans. The shield hauler would push the cans off the shield carrier and into the bucket scoop. The bucket scoop then delivered the cans to the storage area. The fork scoop, with clamp, would then install the cans.

In a typical three entry gate road, using 60° angled crosscut, the logistics surrounding the can must be examined and streamlined to ensure an efficient operation. Since the cans must be hauled one at a time using the clamp during installation, staging of the cans prior to installations is critical, particularly if the cans are stored 700 to 1300 ft (213 to 396 m) outby the face. The fork scoop with the clamp must travel this distance for each can installed. With 60° crosscuts off the belt entry, storage space in the tailgate entry is limited in order to maintain a tram road. In addition, given the weight of each can, approximately 800 lbs (363 kg), handling of the cans should be kept to a minimum. Prototype attachments combining a scoop bucket and JIB crane with a clamp have been developed to preform the delivery and installation functions in the same operation.

CONCLUSIONS

Several alternative technologies to conventional wood and concrete cribbing have been developed in recent years. These new support technologies provide improvements in supporting capability as well as material handling and travelway advantages. However, since their supporting characteristics are all different, a design methodology must be developed in order for mines to safely employ these technologies and to maximize their benefits without increasing the overall cost of support. ***Conservative applications or trial and error assessments are no longer practical nor prudent for state-of-the-art longwall mines.***

The design methodology proposed in this paper and examined through a field trial at a western Pennsylvania coal mine embodies a fundamental concept of rock mechanics, that being the "ground reaction curve". This methodology will allow operators to ***optimize the use of these new support technologies*** and provide an engineering means to compare the performance of alternative support strategies on an equivalent basis. The NIOSH Wood Crib Performance Model is currently being upgraded to a windows format. Included in this new version will be the addition of the performance characteristics of alternative support technologies such as those discussed in this paper. In addition, a subroutine will be provided that incorporates the longwall tailgate design methodology proposed in this paper. This program will facilitate the use of this design methodology and will allow mines to optimize the use of any support technology once a ground reaction curve for that mine particular is identified.

Four alternative standing support technologies were installed at the western Pennsylvania mine: (1) The Can Support (Burrell Mining Products), (2) the Alternative Crib Support (Heintzmann Corporation), (3) Pumpable concrete support (HeiTech Corporation), and (4) the Propsetter (Strata Products USA). Ground conditions for all these support applications were generally very good, which is consistent with the measured ground reaction behavior and installed support density.

Material handling activities associated with support construction are responsible for many musculoskeletal injuries to mine workers. This trend is likely to grow as the mining work force is aging. Most alternative support technologies provide material handling advantages of one form or another. For example, they all require less work per ton of support capability than the conventional 4-point wood cribbing and steel fiber reinforced concrete support systems. Engineered timber supports such as the Strata Products Link-N-Lock crib reduce the construction work required per ton of support by 69 pct compared to conventional 4-point wood cribs. Even further reductions (up to 92 pct) can be realized by using a support such as The CAN, which is installed primarily by a machine with minimal manual labor. Prop type supports such as the Propsetter and ACS also significantly reduce the construction work per ton of support capability.

Minimizing the volume of material used in secondary support can dramatically reduce the transportation requirements for secondary roof support construction. Prop type supports such as the Strata Products Propsetter or the Heintzmann ACS also provide an advantage in this regard in that only 2-4 pieces are required for installation compared to 24-36 pieces required for conventional wood cribbing. The bag used in the Pumpable Support developed by Heintzmann can easily be carried to remote locations such as bleeder entries and installed among existing supports when necessary to provide supplemental support.

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APPENDIX A

LABORATORY PERFORMANCE DATA FOR NEW SUPPORT TECHNOLOGIES

The load-displacement characteristics of numerous roof support technologies have been determined at the NIOSH Safety Structures Testing Laboratory through full scale testing in the unique Mine Roof Simulator load frame (2). The load-displacement response of these various support systems are documented in figures A1 through A6, grouped by the following description of the support type: (a) conventional wood cribbing (figure A1), (b) engineered wood crib supports (figure A2), (c) conventional and engineered timber post supports (figure A3), (d) deformable concrete supports (figure A4), (e) non-yielding concrete supports (figure A5), and (f) yielding steel supports (figure A6).

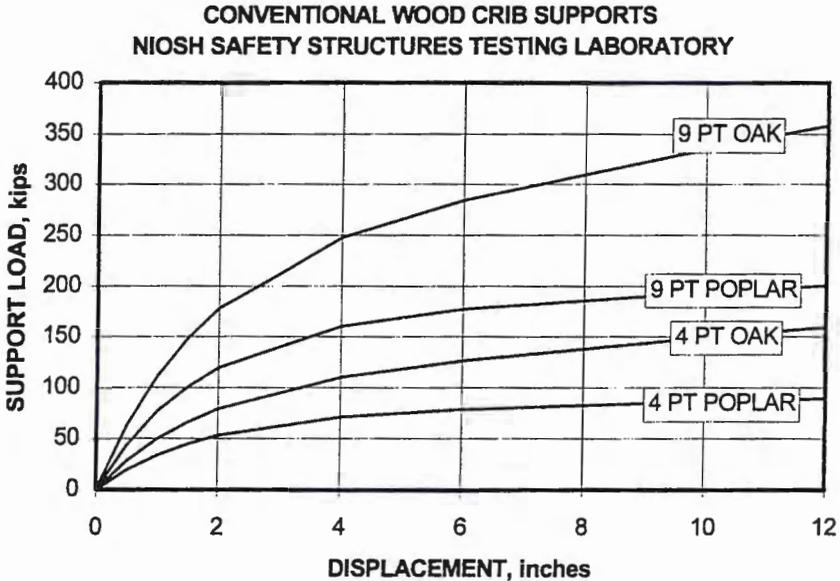


Figure A1. Load-displacement performance data for conventional wood crib supports.

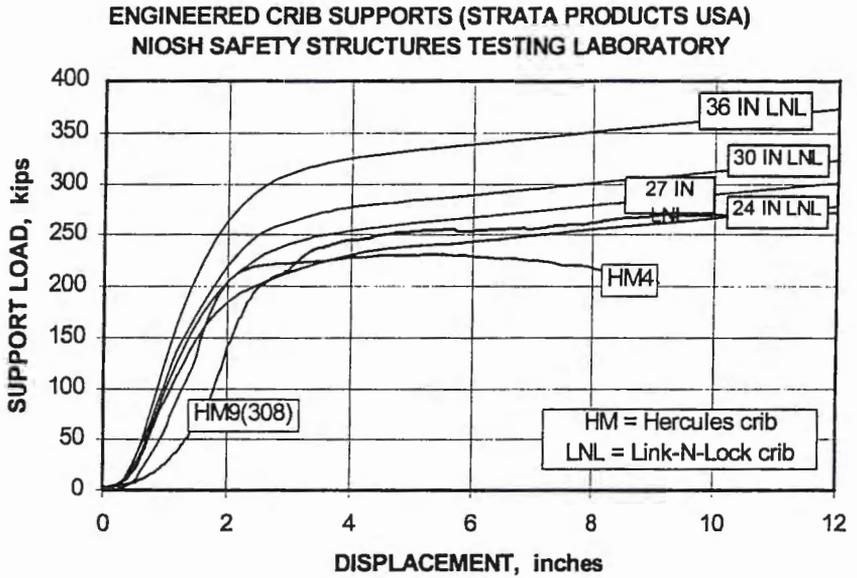


Figure A2a. Load-displacement performance data for engineered wood crib supports.

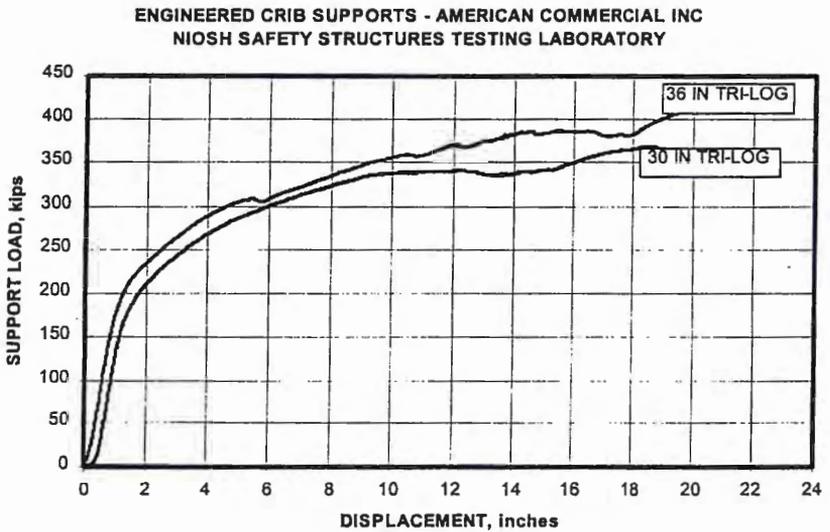


Figure A2b - Load-displacement data for engineered crib supports.

**CONVENTIONAL AND ENGINEERED TIMBER POSTS
NIOSH SAFETY STRUCTURES TESTING LABORATORY**

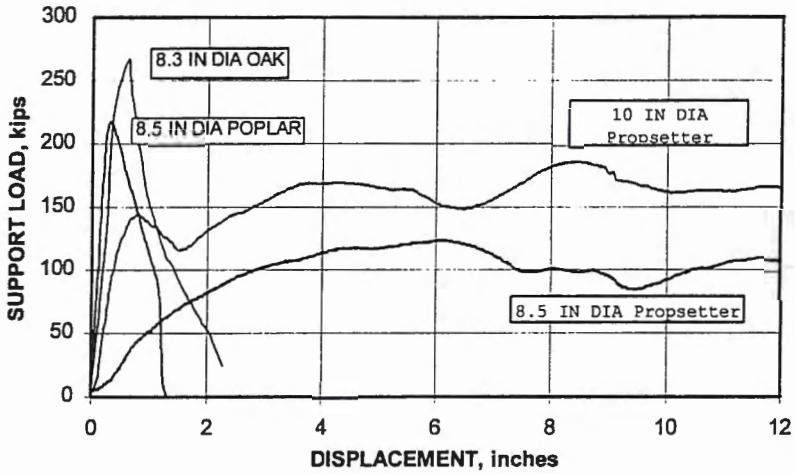


Figure A3. Load-displacement performance data for conventional and engineered timber props.

**DEFORMABLE CONCRETE SUPPORTS
NIOSH SAFETY STRUCTURES TESTING LABORATORY**

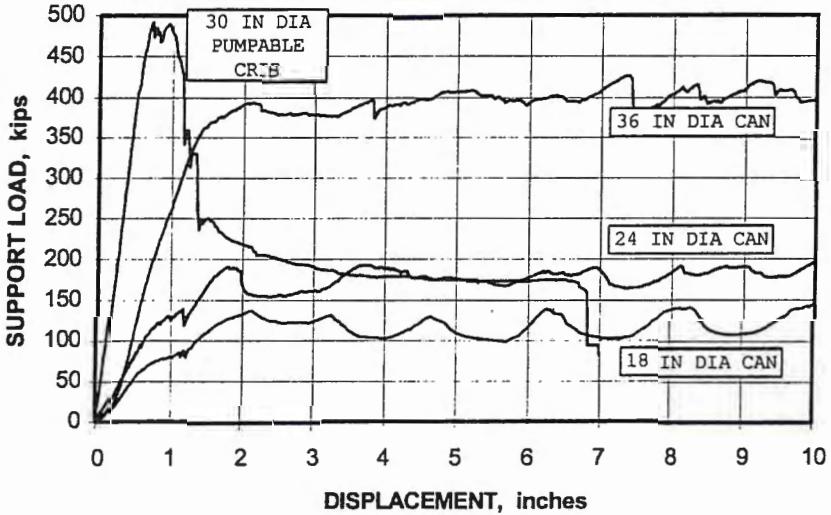


Figure A4. Load-displacement data for deformable concrete supports.

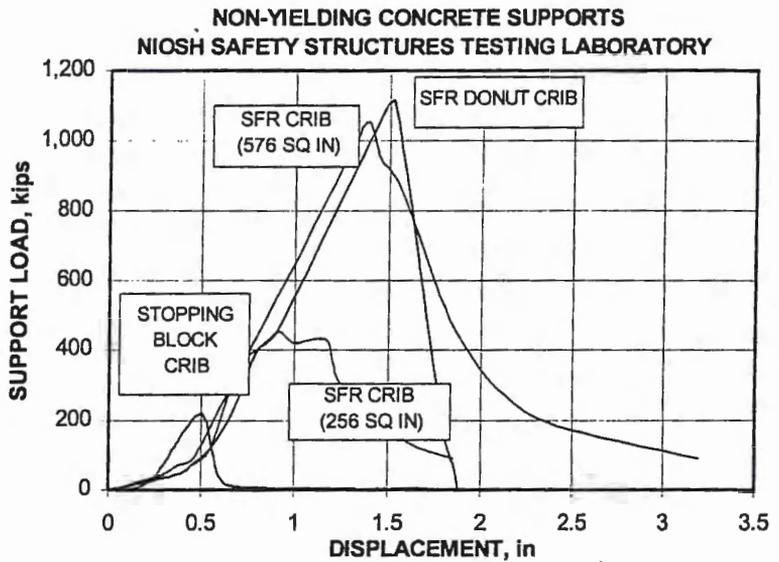


Figure A5. Load-displacement performance data for non-yielding concrete supports.

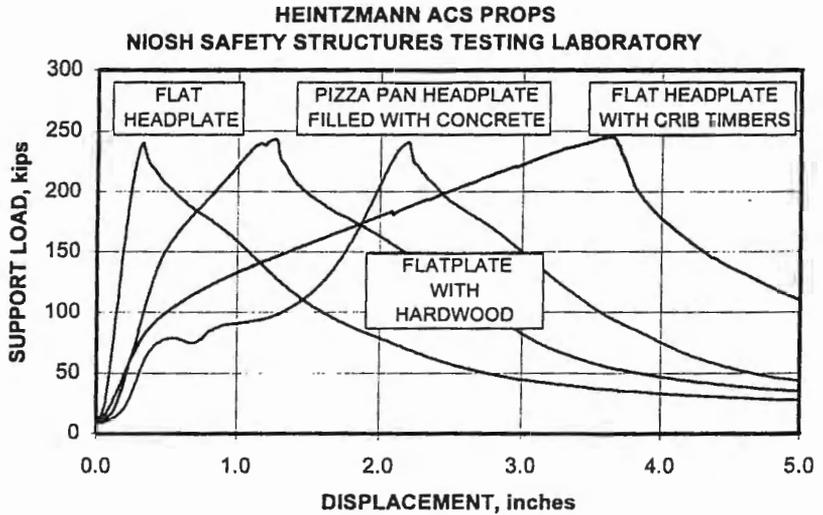


Figure A6. Load-displacement performance data for yielding steel supports.

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