

# Shield Design, Construction and Operation

**Thomas M. Barczak**  
Research Physicist

**Gregory J. Chekan**  
Mining Engineer

**Daniel R. Babich**  
Mining Engineer  
National Institute for Occupational Safety and Health  
Pittsburgh Research Laboratory

### \*\*\* ABSTRACT

The success of longwall mining can largely be traced to the development of shield support. The most obvious trend in shield design has been an increase in shield size and capacity. The other major improvement has been in electro-hydraulic control technologies. This paper examines these design practices in relation to shield selection and capacity determination philosophies, and the consequences of these design practices on capability of the longwall shield to provide effective ground control. Issues related to the setting loads and support stiffness are discussed in detail. Laboratory performance testing of shields can be critical to a successful new shield design and invaluable in assessing the life expectancy of aging shields. NIOSH has recently opened its Safety Structures Testing facility at the Pittsburgh Research Laboratory for shield performance testing, providing unique capabilities using the Mine Roof Simulator (MRS) load frame. Retirement criteria for aging longwall shields are examined and factors that lead to premature failure of shields are discussed. Hydraulic problems are experienced by virtually every longwall shield at some point in their operating life. These hydraulic problems can result in no support capacity, yet many hydraulic failures go undetected since the leaks are internal to the leg cylinders. Methods to identify and diagnose these hydraulic problems are provided in the report. In summary, this paper provides a good overview of the issues that impact the design, construction, and operation of modern longwall shields.

### \*\*\* INTRODUCTION

Throughout the history of longwall mining, the design of the roof support system has been critical to the success of the mining operation. Early forms of longwall mining used wood props for face support and packwalls made from roof and floor rock to control caving of the immediate roof (1). These systems were replaced by powered roof supports that could be advanced easily while allowing the strata to cave behind them. The first powered roof supports were simple frame and chock structures. These designs were poor in their ability to resist horizontal displacements and moment loading caused by the strata dynamics during the caving process. They often experienced difficulty and failure (2). The shield greatly improved kinematic stability by providing a horizontal stiffness by mechanically connecting the canopy to the base in a truss-like fashion. The success of the shield support promoted the application of the longwall mining method in highly faulted and massive strata conditions where caving was difficult to control and where chock and frame supports were inadequate.

The basic shield design has changed little since its inception in the 1970's. The primary change has been a steady increase in shield capacity, resulting in larger hydraulic cylinders and support structures. The consequences of the "bigger the better" design philosophy are examined in the paper. The question is how much capacity is needed and why? The design requirements from a ground control perspective are analyzed to help mine operators make this decision, but the rationale for higher capacity supports is often based more on

enhancing life expectancies than on ground control issues. The consequences of high capacity designs are also examined from this perspective.

The other major change has been an evolutionary improvement in electro-hydraulic control systems to improve setting capabilities and reduce the time requirements for shield advance. These computerized systems also provide more capabilities to monitor shield loading and diagnose poor performance than ever before. The latest electro-hydraulic control technologies are described in the paper, pointing out differences in philosophies among the shield manufacturers.

There has also been a definite trend in the United States toward two-leg shield designs. The paper discusses the reasons why two-leg shields provide superior roof control compared to four-leg shields, and examines the design issues in two-leg shields specifically in relation to their ground control performance capabilities.

One of the most agonizing decisions mine operators have to make is when to retire their current shields and purchase new ones. At a cost for a new face of upwards of 25 million dollars, this is not an easy decision. Factors that contribute to shield failure and criteria for shield retirement are examined in the paper to assist mine operators in this difficult decision. One aspect of the shield performance that is often overlooked is the condition of the hydraulic cylinders. A program to assess hydraulic cylinder component leakages is outlined in the paper.

A critical element in assessing the performance of new shield designs as well as the integrity of aging shields is full scale performance testing under controlled load conditions. Advanced shield performance testing procedures have been developed at NIOSH's Safety Structures Testing facility using the unique capabilities of the Mine Roof Simulator load frame. These tests are designed to provide a realistic simulation of the in-service load conditions so that an accurate assessment of the shield's structural integrity and hydraulic performance can be made to evaluate the safety of continued operation of aging supports and the design of new shields.

In summary, this paper provides a good overview of current shield technologies relative to their design, construction, and operation. Practical information is provided to help operators understand the design and operational issues that will allow them to make more informed decisions on when to retire old shields, how to select the best new shield, and how to optimize the utilization of shield technology to provide effective ground control in longwall mining.

### \*\*\* STRATA INTERACTION AND SHIELD DESIGN REQUIREMENTS

The selection and design of longwall roof supports are governed by anticipated strata movements and deformations for the particular mine geology where the shield is to be employed. The stability and behavior of roof strata is largely dependent upon the thickness and geologic features of bedded rock layers and the stiffness of the ground supporting elements. Most of the roof structure is capable of maintaining a dynamic equilibrium as the longwall face advances by transferring its weight primarily to the solid coal in front of the face and the compressed portion of the gob behind the face. The immediate roof strata are less stable and cave after the supports are advanced. The powered supports develop load in response to the deformation of this rock mass when it produces convergence and lateral movements of the mine roof and floor at the longwall face.

#### SUPPORT AND STRATA INTERACTION

The strata behavior can be grouped into four basic categories: (1) main roof deformation, (2) periodic weighting; (3) face-to-waste movement of the immediate roof, and (4) deflection of the immediate roof beam (see figure 1). An assessment of the support and strata interactions for these categories is described below.

**Main Roof Deformation** -- The face convergence produced by the main roof behavior is irresistible in terms of any shield capacity that conceivably could be provided. Hence, it is concluded that the shield has no influence on main roof convergence. The load development in the shield will simply be a function of the stiffness of the support. Hence, in terms of main roof loading, the setting pressure should be minimized to prevent excessive yielding of the support.

**Periodic Weighting** -- Periodic weighting is most likely to develop in the partial caving zone several tens or hundreds of feet from the coal seam. The support does not generate sufficient force to significantly affect the state of stress in the rock mass at this level. Hence, it is unlikely that the magnitude of the shield resistance will have much effect on controlling periodic weighting. However, since the periodic weighting can significantly add to the loading on the support, it should be considered in the yield capacity requirement for shields.

**Face-to-Waste Movement of The Immediate Roof** -- The front abutment pressure creates vertical fractures in the immediate roof strata, often creating a disjointed beam, or isolated blocks of rock that become detached along bedding planes from the main roof structure. These blocks or layers of strata are then likely to displace toward the gob as the roof beam becomes distressed due to the removal of the coal and the loss of horizontal confinement. Since the fractures are created primarily by the front abutment pressures, the shield

capacity will have little effect on the formation of the disjointed roof beam, but it can have a big influence on the stability of the roof beam. The face-to-waste horizontal stiffness of the shield can influence the stability by providing extra confinement. This confinement is critical to the prevention of cavity formation and falls of ground in front of the shields, which in addition to degrading the immediate roof stability, create advancement problems for the longwall shields.

**Deflection of The Immediate Roof Beam** -- The integrity of the immediate roof beam may also be enhanced by actively setting the shields against the mine roof and floor. This initial setting force acts to prevent slippage along bedding planes by increasing the frictional restraint between layers. The effect of these actions is to increase the bending stiffness of the roof beam, which reduces its deflection and subsequent shield loading. Structural mechanics indicates that the deflection of the immediate roof beam decreases with increased shield stiffness. Hence, the roof-to-floor (vertical) stiffness of the shield can also be an important design consideration for longwall shields.

## **SHIELD DESIGN REQUIREMENTS**

These interactions of the support with the strata impose the following design requirements for the shield.

1. Adequate capacity to provide equilibrium of the immediate rock mass that is not supported by the coal face or caved gob material.
2. Setting force that will increase frictional restraint between rock layers without fracturing or otherwise damaging the immediate roof structure.
3. Vertical stiffness and hydraulic yield capacity that is compatible with the required setting forces and imposed irresistible displacement of the overburden to avoid excessive yielding of the leg cylinders.
4. Active horizontal loading and passive horizontal stiffness to provide resistance to face-to-waste strata displacements and rotations that compromise the integrity and stability of the immediate roof structure or the stability of the support structure.
5. Sufficient lateral stiffness to maintain stability against loading parallel to the face line that may occur for eccentric contact conditions, pitching seam operations, or horizontal stress fields.
6. Adequate bearing areas at the roof and floor interface to avoid further fracturing, compacting, or movement of the strata that would compromise ground control or support stability.
7. Ability to provide adequate roof and gob cover to avoid the hazardous infiltration of roof material into the working area.

8. Structural components designed to maintain elastic response for load conditions induced by vertical and horizontal strata displacements under full and partial contact configurations established at the roof and floor. Well-engineered mechanics should be employed to avoid critical load conditions.
9. Ability to provide adequate ground control and accommodate changes in operating height.

## STRATEGIES FOR SHIELD CAPACITY DETERMINATIONS

### HISTORICAL PERSPECTIVE

Several models have been developed over the years to determine support capacity requirements. A brief historical perspective is provided below.

**Detached Block Models** -- Historically, the capacity requirements for the design of a longwall shield have been based on assessing the maximum caving height of the immediate roof. Wilson was the first to promote these concepts back in the early 1970's (3). A caving zone occurs when a portion of the immediate roof is fractured by the overburden pressure, causing that portion to separate from the overlying rock mass and cave behind the supports once the shields are advanced. Upon caving, these strata consume a larger volume by bulking to fill the void created by the extraction of the coal seam. This typically establishes a caving height of four to six times the mining height for weak- to moderate-strength immediate roof geologies. More competent strata, which are less likely to be rubblized by the overburden pressure, tend to fail along well-defined parting planes and to cave in larger, blocky pieces with considerably less bulking than weaker strata. Caving heights of up to 12 times the mining height are typical for these competent roof geologies that are frequently encountered in the United States. As a worst-case load condition, it is then assumed that the entire weight of the rock mass in the caving zone must be carried by the shield. This establishes the design capacity for the support (see figure 2). Figure 3 indicates the maximum caving height that can be supported by the indicated two-leg shield capacity, assuming an isolated rock mass 20 feet long and 5.7 feet wide with a caving angle of 30 degrees to vertical at the rear of the support. A shield leg angle of 20 degrees and a rock density of 165 lbs/ft<sup>3</sup> were also assumed in these calculations.

**Periodic Weighting Models** -- Another approach is to estimate the impact of periodic weighting on the support loading (4). The goal is to satisfy force and moment equilibrium requirements for series of detached roof beams or isolated blocks of immediate roof rock (see figure 4).

**Stiffness Models** -- Smart was the first to promote a stiffness model to determine longwall support requirements (5). As illustrated in figure 5, Smart suggested that the powered support was one of three yielding foundations which support the immediate roof and bridging beds. The other two elements being the coal ahead of the face and waste (gob) behind the face. The process, as

Smart saw it, was that the powered support requirement is to control the subsidence (convergence) of the roof strata along the longwall face sufficiently to prevent fractures, which are generated ahead of the face line in the upper regions of the immediate roof, from migrating downward to the roof horizon at the longwall face. This is necessary to ensure that the immediate roof does not become unstable, resulting in excessive support loading leading to ground falls in front of the supports. The key to Smart's concept is that the stiffness of the coal and gob largely control the shield loading and design requirements. In particular, Smart hypothesized that the reason American supports were required to be higher capacity than their European counter parts was that the more competent immediate roof structures failed in what he called "controlled parting plane caving" as opposed to the "bulking factor" caving of the weaker European geologies. The result being that the gob material provided very little support and created an even larger cantilevered roof beam that must be supported by the longwall shields.

**Empirical Models** -- Syd Peng and his colleagues developed an empirically-based model in the late 1980's that identifies both capacity and the type of support requirements for longwall mining (6). In 1989, a computer program called DEPOWS (Design of Powered Roof Supports), was developed. The approach taken by Peng was different than all others in that he focused on identifying the setting load requirements first, and then calculated the yield requirements based on an optimum setting load. To do this, Peng developed some characteristic equations which related the setting loads and post-setting load development to face convergence for various roof geological conditions. Essentially, using underground measurements of shield loading, an equivalent stiffness of the shield and surrounding strata was developed as a function of the shield setting load (see figure 6). Regression constants in these field measurements were related to specific mine geologies, which Peng classified relative to the physical properties and strength characteristics of both the immediate and main roof. Peng was also the first to estimate the active horizontal loading requirements for longwall shield supports.

**Structural Plate Theory** -- Mukherjee has developed load prediction models for longwall shields based on structural plate mechanics (7). He hypothesized that the immediate roof structure is best analyzed as a plate supported and clamped by an elastic foundation in different boundary conditions that represent different mine geologies. The concept is to determine the support loading by evaluating the caving distances and strata deflections associated with the plate failure.

**Numerical Modeling** -- Several people have developed numerical models to predict support behavior. The primary limitation of these models historically has been that displacements at the coal face are not well predicted when homogeneous roof material and elastic behavior assumptions are made. Recently, more advanced models, such as MULSIM and LAMODEL have been developed that may allow for better prediction of convergence in bedded roof deposits and more realistic support load estimations in the future (8).

## CURRENT RATIONALE FOR SHIELD SELECTION

While these concepts attempt to capture the support and strata interaction principles, state-of-the-art shield capacities cannot be justified based on these concepts. The reason for this is that a "bigger the better" attitude has prevailed, being promoted by the manufacturers largely due to the demands of mine operators to improve the life expectancy of the shields. Hence, it is this issue (life expectancy) more than the ground control requirements that prevails in current longwall shield design, at least in regards to the yield capacity of the supports.

In addition, it is becoming more evident that the horizontal loading capability of a longwall shield can be as important a design parameter as the (vertical) yield loading capacity. Current support design generally ignores this requirement at least in terms of required horizontal stiffness and active loading capacities.

### \*\*\* RECENT TRENDS IN SHIELD DESIGN

Two fundamental changes in shield design have been made since the introduction of the shield in 1975: (1) the caliper design was replaced with a lemniscate-guided caving shield that maintains a constant tip-to-face distance throughout its operating range; and (2) electrohydraulic control systems which have replaced manual systems to permit remote and automated operation of the shield. The basic shield structure has remained unchanged for the past 20 years, although the structures have grown dramatically in size and capacity. Current trends in powered support design are summarized as follows.

**Material Specifications** -- The German shield companies (currently conglomerated under MTA) have in recent years promoted the use of high strength steels (100,000 psi yield) to minimize component cross sectional dimensions. This trend continues in 1998 with both MTA and Joy Technologies. One consequence of some high strength steel applications is that special welding practices are required (heat control, etc.) making underground repairs more difficult. In addition to the use of high strength steels, numerical modeling is now becoming a standard design practice. These mathematical models are used to analyze stress distributions in the support components to lighten areas that are over designed and strengthen weak areas.

**Capacity** -- Support capacity has continued to increase throughout the history of longwall mining. This trend has continued during the past decade as shown in figure 7 (9). Average support capacities in the United States have increased by 25 pct since 1985 to an average support capacity at yield of 724 tons for the 65 operating longwalls in the U.S. in 1998. Six installations (10 pct) of the current longwalls employ shields with capacities greater than 900 tons, and 19 installations (30 pct) have capacities equal to or greater than 800 tons. The current distribution of shield capacities is shown in figure 8. The highest capacity shield used in the United States is 980 tons (9). As shown in figure 7, maximum

shield capacities have evolved from 800-ton shields which were common from 1985 to 1990 to 980-ton shields which were first installed in 1993. The 980-ton shields require a bore diameter of approximately 360mm.

**Type of Shield** -- There has been a steady increase in the use of two-leg shields in favor of four-leg shields during the past decade as shown in figure 9, and two-leg shields are becoming the favored support world wide. In 1997, 63 of the 65 longwall faces in the U.S. were two-leg shield systems, compared to only 53 pct in 1985. Larger size hydraulic cylinders have been developed in recent years to accommodate the increased demands for higher shield capacities, and have allowed these capacities to be realized with two-leg designs that were not possible 10 years ago.

**Size** --Longwall shields have increased in length to accommodate one-web-back operations and larger face conveyors and deeper shearer webs. In a collapsed position, these units are now 20 to 22 feet in length. The standard canopy width is now 1.75 m, replacing the 1.5 m designs that were prevalent 5 years ago. This trend of increasing canopy width is likely to increase up to 2.0 m widths in the future, which may represent an upper limit with current shield construction materials since wider shields weigh more, thereby requiring more effort to transport during face moves. The potential benefit of wider shields is less cost since much of the cost is due to the machining of the hydraulic leg cylinders, and fewer legs are required with wider supports. However, this cost advantage is being offset by higher capacity systems. The wider supports may also be more stable in thick-seam operations. A decrease in move time might also be realized, since 15 pct fewer supports are employed on a face with the 1.75 m designs.

**Setting Forces** -- Setting forces have increased in proportion to the increase in yield capacity because the size (diameter) of the leg cylinders has increased to accommodate the higher yield capacities, while the hydraulic setting pressures have remained constant in the 4,000 to 4,200 psi range (see figure 10). Most hydraulic power supply systems and electro-hydraulic control technologies still try to maintain a set-to-yield ratio in the 0.6 to 0.8 range. Optimum setting forces as a function of overall support loading and geological conditions are not pursued by current control technologies.

**Component Constructions** -- The component that has changed the most is the canopy. Extensible canopy designs are occasionally used in Europe, where friable roof geologies must be maintained (10). The trend in the United States is towards rigid canopies without any extension or flipper arrangements to control face sloughage. Canopy tips have been curved upward to promote tip contact. However, the force generated at the tip is typically about 10 pct of the leg force and is mostly a function of the distance of the tip from the leg cylinders. The distribution of loading on the canopy and base is also dependent upon the stiffness of these components and the deformation characteristics of the immediate strata. There has been increased usage of solid base configurations to alleviate splaying that occurs with individual base pontoons and to improve

load distribution on the mine floor. Some high-capacity two-leg shields are now using a single-piece base as opposed to a split-base design to increase contact area and reduce toe loading.

**Control Systems** -- Both manufacturers continue to make improvements in the electro-hydraulic control systems. Positive-setting and shearer-initiated control capabilities have generally been improved. Positive-setting algorithms are more sophisticated with pressure monitoring at programmable thresholds to more intelligently achieve full setting, or deactivation if full setting is incapable of being achieved due to some sort of hydraulic failure on a particular leg cylinder. Older-time dependent algorithms (see figure 11), which essentially gave up on trying to achieve full setting after a few seconds, have been replaced by these more sophisticated pressure- monitoring algorithms that will continually try to achieve full set during the entire operational cycle (see figure 12). More flexible and user-friendly programmable control have been incorporated to "custom-design" the automated control capabilities once the system is in operation at the mine. Improvements have been made in face-end control logic to allow for full automation of bi-directional cutting, although many mines still prefer manual operation for the face-end activities. The cycle times for shield advance continue to be minimized. Combinations of multiple functions pertaining to the powered lowering, base lift, and conveyor push of individual shields are now routinely performed at the same time to compress the support advance time requirements. Both infrared and shearer "drive train" tracking systems are available for automated shearer-initiated support advance. The infrared systems require detection sensors to be mounted on each shield, whereas the position detection sensors are mounted only on the shearer for the alternative "drive-train" system. The infrared system tends to be more problematic due to the sensor failures and signal blockages. Shield advancement closer to the shearer is more often achieved with the shearer "drive-train" systems, since the shearer position detection is more reliable. Current computer microprocessors have much more memory for storage of shield performance data than their predecessors, and more sophisticated diagnostic and shield performance assessment capabilities are being developed.

MTA favors the use of the shield control units on every shield. This concept provides redundant capabilities to allow operation to continue when one or more units is not operating. The latest version features an updated PM-4 shield control unit (12). The PM-4 was first introduced in 1992 through the Westfalia group prior to the consolidation of the companies in MTA. Recent improvements have been in the ruggedness of the shield control unit, including an improved keypad design for longer life and an easy to read 16-character LED display. Groups of 15 SCU are connected to a common power supply, which is galvanically isolated from the network. A separate PM-4 server is dedicated to shearer initiation support control, which coupled with a full duplex communication system between shields, provides for reliable and secure automated support advance capability.

Joy favors a more centralized approach. A central computer, called a shield control center (SCC), is housed in an explosion-proof enclosure at the headgate and acts as the brain to control the shield functions through a series (one on each shield) of intrinsically-safe shield interface modules (SIM). The current generation is referred to as RS20. The SIM units feature an ergonomically designed keypad with a diagram of a shield to facilitate activation of the intended support function (figure 13).

**Hydraulic Components** -- Solenoid-operated valving systems are now becoming standard. Spool valves have been shown to be superior to ball and seat designs which are prone to contamination problems. In addition, these systems allow the solenoid to be activated upon demand, unlike previous systems which required the hydraulic feed to be interrupted by a control solenoid. This leads to both quicker and smoother control of support functions.

**Hydraulic Emulsions** -- For many years, longwall shields have utilized a water/mineral oil emulsion as a hydraulic medium for the leg cylinders. The standard system has been a 5 pct oil/water emulsion. There is trend towards the use of synthetic fluids. Most western mines have now switched to "low treatment" systems with synthetic oils in concentrations of only 1 to 2 pct. The motivation for this has largely been due to environmental issues imposed by the Utah Department of Natural Resources. Only one eastern mine is currently using the "low treatment" emulsion system. Fazos (Australia) has experimented with an all-water system.

Although the synthetic oils are environmentally preferred, they also cost significantly more. The synthetic concentrate is about 3 to 5 times the cost of mineral oils. Hence, despite the lower concentration used in the "low treatment" systems where less than 2 pct oil is utilized, the overall cost is typically about 50 pct greater than "high treatment" systems using 4 to 5 pct mineral oil concentrations. The major disadvantages of the synthetic "low treatment" system is that there is little room for error. A small drop in the oil concentration can lead to lubrication and acidity problems. Therefore, maintenance of the oil/emulsion is much more critical than in the "high treatment" systems, where the oil content can be reduced from 5 to 4 pct with little if any detrimental effects. Bacteria growth can also be accelerated in very low concentrations of oil emulsions, which can cause more severe corrosion problems than if there were no oil at all.

There are three major manufacturers of shield emulsions (oil). Century is the major manufacturer which services 55 of the current longwalls and supplies both "high treatment" mineral oil and "low treatment" synthetic oil products. Texaco provides "high treatment" mineral oil only and D.A. Stewart markets synthetic oils only.

### \*\*\* CONSEQUENCES OF DESIGN PRACTICES

#### TWO-LEG VS FOUR-LEG SHIELD DESIGN

As previously indicated, there has been a definite trend toward the use of two-leg shields in favor of four leg shields. The advantages of the two-leg design are summarized as follows (13, 14).

1. The primary difference is the ability of the two-leg shield to provide an active horizontal force (10). Since the leg cylinder in a two-leg shield is inclined toward the face, horizontal components of the leg force push the canopy toward the coal face as shown in figure 14. This induces a force into the immediate strata that tends to alleviate tensile stress developments and propagation of shear failures or growth of existing fractures into the near seam strata directly in front of the shields. In comparison, the front and rear set of legs of a four-leg shield are inclined in opposite directions to one another, and the horizontal components of leg force largely cancel one another out and do not produce an active horizontal force, or even worse the resultant horizontal force may act towards the gob. In conclusion, two-leg shields are more effective in controlling highly jointed or friable immediate roof geologies, since the active horizontal force arrests slippage along fracture planes and improves overall strata stability.
2. A reported advantage of the four-leg shield is that it provides a resultant vertical force farther from the coal face than does a two-leg shield. This is supposed to be more effective in controlling cantilevered strata, since the support force acts at a mechanically more efficient location. However, this advantage is highly overrated for two reasons. First, the difference in resultant locations and the corresponding load profile on the canopy are too small to make a significant difference. Second, there is typically an imbalance in load distribution between the front and rear legs of a four-leg shield with the majority of load carried by the front legs, so that the resultant force location is similar to that of a two-leg shield.
3. The multiple load paths provided by the front and rear legs also make the four-leg shield less effective in cavity prone strata. As the example in figure 15 illustrates, the force in the rear legs cause the canopy to rotate up into the cavity, which causes a loss of roof contact at the canopy tip. This condition ultimately results in further cavity formation and requires the front legs to do all of the supporting work. Since the front legs of a four-leg shield are considerably smaller than they would be in a two-leg shield of equivalent support capacity, the four-leg provides much less supporting force than would a comparable two-leg design. The primary advantage of a four-leg shield is its more uniform and hence lower maximum roof and floor contact pressure.
4. The primary disadvantage of a two-leg shield is generally higher contact pressure on the canopy and base. High toe loading, caused by the moment created by the line of action of the resultant vertical forces acting on the

canopy and base, can be a problem in high capacity two-leg shields and should be a consideration in the support design. Base toe pressures of 600 psi or greater can be expected on high-capacity two-leg shields. Base toe lifting devices are now standard on most two-leg shields to assist in the advancement of the shields particularly in soft floor conditions.

## SETTING LOADS AND SHIELD STIFFNESS

An analysis of shield mechanics indicates that the vertical load capacity of a shield is almost totally provided by the hydraulic leg cylinders. The caving shield - lemniscate assembly has very little vertical stiffness (15). The purpose of this assembly is to provide horizontal stiffness and stability to the canopy and base. Therefore, if the support capacity is to be increased, it must be done through the leg cylinders. Two options are available, if the number of leg cylinders is to remain constant. Either the hydraulic yield pressure can be increased, or the size (area) of the leg can be increased. Historically, the design practice has been to increase shield capacity by increasing the diameter of the leg, while keeping the setting pressures constant at about 4200 psi and the yield pressure constant at about 6200 psi.

An important consequence of the increased leg area is a corresponding increase in shield setting forces. It is widely recognized that the higher setting forces provide greater initial forces against the mine roof that can help to promote caving and strengthen the immediate roof beam by increasing the frictional restraint between rock layers. As previously indicated, the inclination of the leg cylinders in two-leg shields creates a horizontal force component that tends to alleviate tensile stress developments and propagation of shear failures or growth of existing fractures into the near seam strata directly in front of the shields. The question then is how much setting force is needed? Can there be too much setting force? The answer is that there is an optimum setting force; however, determining the ground reaction curve for longwall support and strata interaction is difficult.

Peng attempted to do define setting load requirements based on observed increases in shield loading for different geological conditions (6). He concluded that the minimum setting load is that which fully closes all the gaps in the immediate roof beds such that the equivalent stiffness of the support/immediate roof structure is maximized, causing maximum load development in the shield after the support is set against the mine roof and floor. Increasing the setting force beyond this minimum requirement will reduce post-setting load development, but also increase the final (total) load at the completion of the mining cycle. Hence, there is tradeoff in increasing the setting load beyond the minimum requirement relative to the maximum (yield) load capability of the support (16). Peng recommended that the optimum setting load is in the range of 1.6 times the minimum setting load.

Smart also believes there is an optimum setting load in relation to the active horizontal force developed in two-leg shield designs. He believes that the active

setting load is most effective in competent immediate roof structures, such as the sandstones common in many U.S. mines, that tend to cave in a block manner (17). However, in weak roof structures, excessive horizontal forces may generate increased shear stresses which cause further fracturing of the laminated roof beam. He also makes the point that in laminated beam roof structures, there is likely to be considerable lateral (face-to-waste) displacement of the bedded layers such that the horizontal confinement will be generated during the production cycle by the reactive horizontal stiffness of the shield. Hence, there is no need to create large horizontal forces during the setting operation.

It is also important to recognize that the stiffness of the shield is also increased significantly due to the larger leg diameters. For example, a 500-ton shield has a vertical stiffness of about 400 tons per inch of vertical displacement, while an 800-ton shield has a stiffness of 600 tons per inch of displacement. The increased stiffness has two ramifications regarding the required setting and yield load requirements and how the support interacts with the strata.

- o The stiffer shield will result in more load development for an equivalent roof-to-floor convergence, and thereby impact the optimum setting load and associated yield load requirements necessary to minimize excessive yielding in roof conditions where the supporting force does have a large influence on controlling the roof deformations.

Figure 16 compares load development for the 500-ton shield and an 800-ton shield used in the previous example for the same load condition: 0.5 inches of roof convergence. Since the stiffness of the 800-ton shield (600 tons/in) is 50 pct greater than that of the 500-ton shield (400 tons/in), the 500-ton shield will react 200 tons of load in response to the 0.5 inches of convergence while the 800-ton shield reacts 300 tons of load in response to this convergence. With a setting force of 60 pct of the shield capacity, the full 500 tons of capacity is used in the 500-ton shield and all but 20 tons is used in the 800-ton shield. Hence, both supports were essentially loaded to their full capacity and stressed to the same degree for the identical load condition, despite the 800-ton shield having 300 additional tons of capacity initially. Based upon this analysis, longer shield life and additional reserve capacity to accommodate difficult ground conditions should not be expected with higher capacity shields.

- o Conversely, the stiffer shield may help to minimize roof deformations and improve roof stability, particularly in weaker roof structures, since greater shield forces will be developed with less roof movement. In essence, equilibrium will be attained at less roof movement, reducing the tensile stress developments that result in failure of cantilevered roof beams.

Using the 500-ton support and the 800 ton support as example, the 800-ton support will develop 480 tons of supporting force during setting and an additional 60 tons for each 0.1 inches of roof displacement, while the 500 ton shield will develop 300 tons of setting force and only 40 tons of additional supporting force

for each 0.1 inches of roof displacement. The result would be that the 800 ton shield would not be any different than the 500 ton shield in controlling the initial roof behavior that is often critical to the roof stability. If the 800-ton capacity had been developed by using the same diameter leg and increasing the yield pressures from 6,200 to 9,920 psi, there would no increase in setting force (assuming the same pump pressure) and no increase in shield stiffness.

### **MUTLI-STAGE HYDRAULIC CYLINDER DESIGN**

All current shield designs employed in the U.S. utilize two-stage leg cylinders where the top stage pressure is isolated from the bottom stage pressure by an internal check valve (see figure 17). There are several performance consequences related to the operation of these multi-stage cylinders.

- o The setting force is reduced considerably (typically between 40 and 50 pct) when the bottom stage is fully extended. The bottom stage is fully extended on any operating cycle which establishes a new maximum operation height. When the bottom stage is fully extended, the setting force equals the pump pressure times the area of the top stage.
- o The stiffness of the shield changes as a function of operating height and stage extensions (see figure 18). Generally, the stiffness increases exponentially as the height decreases and can change as much as an order of magnitude from very low operating heights to very high operating heights. Different combinations of staging can produce a range of shield stiffnesses at the same operating height.
- o Yielding will cause a reduction in support force of about 10 pct. During yielding, the support is reduced in height, thereby allowing the roof to lower. Hence, excessive yielding is not desirable. The amount of roof lowering will be dependent of the stiffness of the shield, progressively decreasing as the shield height lowers. As an example, a 700 ton shield will lower approximately 0.03 inches during each yielding event at a mid-height operating range.

### **HORIZONTAL SHIELD STIFFNESS**

The face-to-waste horizontal stiffness of a shield is determined primarily by the stiffness of the leg cylinder in two-leg shield designs (15). The stiffness of the caving shield- lemniscate assembly also contributes to the face-to-waste horizontal stiffness of the shield, but only after the translational freedom in the lemniscate joints due to pin fabrication tolerances and wear is overcome, which is often 1 or more inches of face-to-waste displacement of the canopy relative to the base. Since the leg stiffness has increased in higher capacity shields, higher capacity shields are also more effective in resisting face-to-waste strata movement than lower capacity shields. The horizontal stiffness of the caving shield - lemniscate assembly is not dependent on the size of the leg cylinders,

hence higher capacity shields do not have significantly stiffer lemniscate assemblies.

The face-to-waste horizontal stiffness of a shield is also reduced as the operating height increases due to a more vertical orientation of the leg cylinders and the lemniscate links. Reductions of 50 pct or more are typical for a change from a low operating height to a high operating height for a specific shield (15). The active horizontal force exerted by the horizontal component of the leg forces also decreases as the operating height increases. Hence, two-leg shields are less effective in resisting face-to-waste strata movements at high operating heights than at low operating heights. The normal force should also be considered in the shield design, since frictional forces must be maintained on the canopy to prevent slippage along the canopy surface at low operating heights.

Conversely, waste-to-face stiffness in two-leg shield designs is totally dependent on the stiffness of the caving shield - lemniscate assembly (15). This assembly must control waste-to-face loading induced by the gob material, and also provide stability to the shield whenever the canopy slides along the roof when the frictional contact is lost during face-to-waste horizontal loading.

### **\*\*\* DESIGN INNOVATIONS FROM ABROAD**

Fazos (Australia) has developed an innovative leg cylinder design (see figure 19) that provides a constant setting force throughout the operating range of the support. Unlike the multistage designs that are utilized by Joy Technologies and MTA which cause a reduction in setting forces of 40 to 50 pct when the bottom stage is fully extended, the Fazos design provides for full setting forces in all cases. Rather than using two stages in series with the pressure in the bottom stage isolated from the pressure in the top stage by an internal check valve, the Fazos design incorporates a unique arrangement of stages where the same pressure occurs in both stages. This has several advantages:

1. Since there is no pressure multiplication in the upper stage, the cylinder structure can be designed with lighter and thinner cross sections.
2. There is no internal check valve to leak and cause loss of support capacity.
3. The design does not require any internal valves in order to extend or retract the second stage.
4. Due to the fact that the first and second stage volumes are physically connected together, the leg is capable of absorbing more energy during roof bumps or dynamic support loading. In addition, externally fitted high volume relief valves can be used to provide superior protection against these dynamic loads.

The one disadvantage may be a lower stiffness. Information on the stiffness of the cylinder was not available for this report. Plans are being made to have

one of the cylinders and perhaps a longwall shield marketed by Fazos tested at the NIOSH Safety Structures Testing facility.

### **\*\*\* PERFORMANCE TESTING CONSIDERATIONS**

NIOSH has recently opened its Safety Structures Testing facility at the Pittsburgh Research Laboratory for shield performance testing, providing unique capabilities using the Mine Roof Simulator (MRS) load frame (18) shown in figure 20. The MRS is an active load frame that more accurately simulates the in-service load conditions than static load frames. It is the only active load frame in the United States with sufficient size and load capacity to accommodate shield testing. The MRS provides realistic and cost effective shield evaluation by combining both vertical and horizontal (racking) loading into a single load cycle; whereas, several load cycles would be required to obtain this loading in a static frame. In addition to these advantages, NIOSH acts as an independent research organization to provide an unbiased assessment of shield performance.

### **SIMULATION OF THE IN-MINE SERVICE CONDITIONS**

There are two basic aspects to shield loading. The initial load condition is determined by actively setting the shield against the mine roof and floor. Subsequent loading is produced by the movement of the surrounding strata during the caving process and the associated internal forces developed within the support structure.

As the shield is set against the mine roof and floor, there is a tendency for the canopy to be displaced horizontally relative to the base. This is due to the resultant horizontal component of the leg forces, which causes either slippage of the canopy along the roof interface or displacement (compaction) of the fractured strata or debris immediately above or below the shield. The Mine Roof Simulator accurately simulates this behavior by allowing the floor of the load frame to move horizontally to transfer the horizontal load developed in the load frame to the caving shield-lemniscate assembly. When a shield is tested against a rigid frame, the canopy and base are restrained from horizontal movement. This restraint eliminates load development in the caving shield - lemniscate assembly from horizontal displacement of the canopy relative to the base, and therefore does not properly simulate the in-mine service conditions.

Once the shield is set against the mine roof and floor, load development within the shield is controlled by: (1) the contact configuration established with the mine roof and floor; (2) vertical displacement of the canopy relative to the base induced by deflection of the main roof beam and weight of fractured immediate roof strata being supported by the shield (see figure 3); (3) face-to-waste movement of the immediate roof as the strata breaks into disjointed blocks from the face abutment loading and loss of confinement; and (4) waste-to-face

loading induced by gob material acting on the caving shield and/or the internal forces developed within the shield due to the leg forces and component reactions.

## **NIOSH STANDARDIZED SHIELD TEST PROCEDURES**

### **TEST SERIES I -- Transfer of Horizontal Load To The Caving Shield-Lemniscate Assembly**

**Objective** -- Minimize external horizontal load acting on the shield to ensure that horizontal components of the leg forces are transferred to the lemniscate links, thereby maximizing load development in the caving shield - lemniscate assembly.

**Test Requirements** -- The canopy must be free to displace horizontally with respect to the base to allow the caving shield - lemniscate assembly to participate to a degree consistent with underground shield behavior. This is accomplished by commanding the floor of the load frame to move horizontally with respect to the roof in a direction and magnitude consistent with the resultant leg force. Main roof loading and deflection of the immediate roof beam are simulated by controlled vertical displacements. The applied displacement and associated shield response is shown in figure 21. The test procedure is as follows:

#### **Test Procedure**

1. A four-point contact on the corners of the canopy and base is used to maximize bending produced by the increase in leg pressure. A three-point canopy contact where one of the rear contacts is removed can also be used to further intensify stress development in the canopy. Base contacts are confined to the outside area of the base pontoon. This induces a tendency for the base section to rotate along its longitudinal axis, causing maximum loading of the bridge section which connects the two base pontoons together.
2. The shield is set against the load frame roof and floor at approximately 2,500 psi leg pressure using an external hydraulic power supply.
3. The floor of the load frame is moved horizontally in a direction that eliminates the horizontal load reacted by the load frame during the setting operation, which causes this horizontal load to be transferred to the shield components. The elimination of the external horizontal restraint moves the resultant force acting on the base forward, which intensifies toe loading, a critical load condition for two-leg shields.
4. Cyclic loading is initiated by a controlled vertical and horizontal movement of the load frame lower platen, inducing a combined vertical and waste-to-face displacement of the canopy relative to the base. The horizontal platen movement is calibrated to minimize horizontal load restraint provided by the

load frame throughout the loading cycle. For two-leg shields, this requires the canopy to be displaced in a faceward direction at a rate that is proportional to the increasing horizontal component of the leg force developed from the vertical closure. The result of these actions is that the caving shield - lemniscate assembly is fully loaded to provide internal equilibrium within the shield.

## **TEST SERIES II -- Eccentric Twisting and Racking of the Canopy**

**Objective** -- To maximize loading in the various shield joints and component clevises.

**Test Requirements** -- The requirement for this test is to induce a resultant load vector that produces both face-to-waste racking and twisting of the canopy with respect to the base. The caving shield - lemniscate assembly is designed to alleviate the hydraulic leg cylinders from bending moments by absorbing all horizontal loading acting on the shield. Joint wear is the most common problem that causes premature shield retirement. Excessive joint wear occurs when horizontal loading increases the friction in the joints. The joints of longwall shields are designed for a single degree of freedom, that being rotation along the centroidal axis, much like a person's knee functions. Stress on the connecting pins is intensified when the canopy twists (rotation in the plane of the canopy) causing partial contact of the connecting pins within the clevis.

### **Test Procedure**

1. The four-point contact on the corners of the canopy and base is again used to maximize bending in the canopy and base sections.
2. The shield is positioned in the load frame such that the direction of applied horizontal displacement (loading) is along a diagonal line from the one front corner to the opposite rear corner of the canopy as shown in figure 22. As seen in the figure, the resultant force is composed of lateral ( $\delta y$ ) and horizontal ( $\delta x$ ) components that produces face-to-waste displacement and twisting of the canopy with respect to the base.
3. The shield is set against the load frame roof and floor at approximately 2500 psi leg pressure.
4. Cyclic loading is initiated by the active load frame applying a combined face-to-waste and vertical displacement of the canopy relative to the base. Vertical displacement is applied to the degree necessary to sustain the horizontal loading. Horizontal displacement is applied until the legs reach yield load. Since the horizontal displacement is opposite that of Test Series I, the lemniscate link force is also opposite with the front link acting in tension and rear link acting in compression. This change in state of stress produces maximum wear and fatigue loading. Figure 23 depicts the load configuration for the lemniscate link pins. As seen in the figure, the eccentric loading

causes the pins to tilt within the worn clevis, causing point contact which intensifies the stress on the clevis and connecting pins of these joints.

5. The procedure is repeated with the shield positioned such that horizontal loading occurred along the opposite canopy tip to rear diagonal (see figure 22). This causes opposite twisting of the canopy and racking of the component pins and clevises.

### **TEST SERIES III -- Leg Socket Shear Tests under Constrained Shield Conditions**

**Objective** -- Maximize shear stress development in the leg socket welds and castings.

**Test Requirements** -- Failure of the leg sockets is a common shield problem. An example of a base leg socket failure is shown. Failure can occur from flexure of the canopy and base, but the most severe loading is caused by shear stress in the leg socket castings. Canopy and base bending is provided in both Test Series I and II. The requirement for this test series is to induce direct shear stress in the leg socket casting weldments without wasting energy in canopy and base deformation.

#### **Test Procedure**

1. The shield is positioned in the load frame at its maximum underground operating height since the vertical component of the leg force increases as a function of height. Canopy and base contacts are positioned just outside the leg socket. This configuration induces maximum shear stress in the leg socket casting since all of work is done through the transfer of applied loading directly to the leg cylinders. This configuration requires that the canopy and base need to be restrained from any horizontal movement to maintain shield stability during loading.
2. Then the shield is actively set against the load frame roof and floor at approximately 2500 psi leg pressure.
3. Cyclic loads are applied by controlled vertical displacement of the load frame platens. The shield is cycled between the setting load and yield load.

### **\*\*\* RETIREMENT CRITERIA AND FACTORS THAT CAUSE SHIELD FAILURES**

The life of a shield is determined primarily by the number of operating cycles and the in-service load conditions. State-of-the-art longwall shields are generally under warranty for a period of 5 years. This warranty protects against structural and hydraulic component failures that render the support inoperative or significantly degrade the performance capability of the support. Obviously, the

number of operating cycles that occur in a five year period depend on the production rate. Based on the 1995 production data, an average longwall will produce 2.6 million tons per year (19). Assuming a 33-in cut for each shearer pass on a 820-ft face and a 6.8-ft seam height, this translates into approximately 4,200 shield operating cycles per year or 21,000 cycles in a 5 year period. For comparison, a 5 million ton per year mine would develop twice as many operating cycles or approximately 40,000 during a 5 year period.

Structural failures are typically due to fatigue (20). Unfortunately, fatigue failures are like a time bomb waiting to explode; there is little and often no warning that they are about to happen. The risk of failure increases dramatically as the shields near the end of their useful life. The only meaningful method to determine the remaining life expectancy of used shields is to have them performance tested. Ideally, they should be evaluated near the end of the manufacturers warranty period to resolve any problems that have developed without notice.

For a well-designed shield, the most likely structural condition that forces a retirement decision is excessive wear in the joints that connect the various components together. The manufacturing design tolerance is generally around 2.5 mm. The shield manufacturers typically recommend that the joints be rebuilt when an additional 2 to 3 mm of joint wear occurs. The joints can be rebuilt by welding, but the preferred approach is generally to use enlarged pins. Excessive wear in the joints reduces the supports capability to resist face-to-waste strata movement. In essence, the freedom in the joints must be eliminated through horizontal displacement of the canopy relative to the base before the caving shield - lemniscate assembly develops any horizontal stiffness. Figure 24 shows that 5 inches of horizontal displacement was required on a 700-ton longwall shield with 1 to 2 mm of wear in various shield joints.

While there are relatively few shield failures these days, premature failures still do occur. In 1997, two longwall faces were experiencing base failure problems and one longwall face had severe hydraulic problems resulting in ballooning of the leg cylinders. Several factors can lead to premature failure of state-of-the-art shield supports. These factors are summarized as follows:

**Poor Quality Control** – One of primary causes of premature failures is poor quality control during the manufacturing process. Poor quality control can occur in any of the manufacturing steps. Some examples include improper welding techniques resulting in poor quality weldments, fabrication tolerances which do not meet design specifications, and poor quality steel that does not meet the material strength requirements.

**Inadequate Performance Testing** – Performance testing of the support prototype plays a critical role in identifying design deficiencies before the shield goes into production. The most common problem with performance testing procedures is that they do not properly simulate the in-service load conditions, usually in relation to horizontal displacements of the canopy relative to the base

that transfer load to the caving shield - lemniscate assembly. The NIOSH standardized shield testing program utilizes the unique Mine Roof Simulator load frame to provide performance testing procedures that provide a realistic simulation of load conditions.

**Numerical Modeling Errors** -- Numerical can be a powerful tool to optimize the design of the shield structure, but it is critical that the models accurately reflect the load conditions and structural response of the shield. Most mistakes are made in poor boundary condition assumptions that cause errors in the loading conditions. The most difficult aspect to model is the behavior in the joints which connects the various components together. It is also critical that the structural models accurately model the stiffness of the individual components.

**Corrosion** -- Corrosion is probably the least recognized factor relative to the premature failure of shields. Corrosion can affect both the hydraulic and structural components. The hydraulic emulsions need to be properly maintained to avoid low oil concentrations which in addition to reducing lubrication can lead to acidic water conditions particularly with the use of low concentration synthetic fluids. The acidic emulsion can cause premature rusting and pitting of the cylinder bores and piston rods. Corrosion can also contribute to structural problems. For example, the lemniscate joints bores become pitted (see figure 25) which causes stress concentrations that lead to accelerated wear and failure of either the joint clevis or pin. Corrosion can also be a factor in base failures as the base structure is often submerged in water or buried in wet mine debris.

### \*\*\* CAUSES AND DETECTION OF HYDRAULIC FAILURES

Eventually, all longwall shields including modern state-of-the-art shields, will experience some form of hydraulic problem that will diminish the support capacity and require maintenance to correct. Hydraulic problems can be related either to the electrohydraulic control system or to component failures within the hydraulic cylinders that result in pressure losses. Hydraulic problems are much more likely to occur earlier in the life of the shield than any structural problem. This is not to suggest that the hydraulic designs are deficient, but simply reflects the difference in life expectancy for the hydraulic components compared to the structural components. Fortunately, the hydraulic components can be rebuilt to original design specifications, while structural problems often dictate the retirement of the shield.

The electrohydraulic control systems have improved dramatically since their inception with greatly reduced mean time to failures of the electronics and solenoid-controlled valving. Operational times are now routinely better than 95 pct with these systems.

All longwall shields employed in the U.S. use two-stage hydraulic cylinders. Any condition that results in pressure loss will reduce the capacity of the shield. In many cases, the pressure loss will be internal such that the fluid loss is not

noticeable. The major components of a hydraulic support system were identified in figure 17 as follows: (1) bottom stage piston seals, (2) upper stage(s) piston seals, (3) pilot operated check valve, (4) yield valve, (5) staging check valve(s). Leakage in any of these components will result in the exponential decay of pressure with time to **zero**, meaning the support will have **no** load carrying capability after a certain amount of time.

Observations of the relative positions of the cylinder staging can be used to identify cylinder problems and the cause of hydraulic leakages. As previously described, these leakages are often internal with no visible signs of external fluid leakage. The first indication of internal leakages is when the bottom stage is consistently fully extended. The bottom stage should be fully extended **only** on operating cycles which establish a **new maximum operating height**. Hence, on the majority of operating cycles, the bottom stage should not be at full extension. Another indication of problems is when there is a large difference in the bottom and top stage extensions of adjacent leg cylinders, particularly cylinders on the same support. Some differences in extension may result from uneven roof heights across the width of the canopy, but these differences in bottom and top stage extension should be small and will tend to balance themselves out over the course of many operating cycles. A large difference, such as those shown in figure 26, is an indication of a hydraulic leak that can result in no support capacity. Table 1 depicts the stage movements associated with each component failure (leakage). For two-stage hydraulic cylinders, it is noticed in this matrix that the bottom stage displaces upward or downward due to specific problems, while there is relatively no movement in the top stage. This matrix can be used to provide insight into the nature of the problem. For example, when the bottom stages are consistently fully extended, the matrix indicates that this condition is likely caused by a bad staging check valve or bad top stage seals. Likewise, bad bottom stage seals will likely result in the bottom stage being significantly extended less than normal.

Table 1. Relative movement and resulting hydraulic pressure of the bottom and top stages for a two-stage hydraulic cylinder for specific component failures (source of leakage) for static loading conditions.

<b>COMPONENT FAILURE</b>	<b>Top Stage Movement</b>	<b>Bottom Stage Movement</b>	<b>Bottom Stage Pressure</b>	<b>Top Stage Pressure</b>
<b>Staging check valve</b>	None	Up	0	0
<b>First stage seals</b>	None	Down	0	0
<b>Second stage seals</b>	None	Up	0	0
<b>Pilot operated check valve</b>	None	Down	0	0
<b>Yield Valve</b>	None	Down	0	0

Combinations of component failure will produce a resultant movement of the bottom stage that depends on the pressure changes in the bottom and top stage. For example, failure (leakage) of the bottom stage seals causes the bottom stage to move down, while failure (leakage) of the top stage seals causes the bottom stage to move up. If the leakage rates are equal, the bottom stage will move up if the volume of the bottom stage is greater than the volume of the top stage and the bottom stage will move down if the volume of the top stage is larger than the volume of the bottom stage.

Problems with the staging check valve can be isolated by fully collapsing the shield and monitoring the leg pressures on the operating cycle after the support is reset against the mine roof and floor. The requirement is to have the bottom stage fully extended when the support is reset. In this configuration with a staging check valve that is functioning properly, the pressure in the bottom stage will not change significantly until the force in the top stage due to additional roof loading overcomes the setting force developed in the bottom stage (see figure 27). An immediate increase in pressure in the bottom stage indicates that the check valve is leaking sufficiently to not allow the pressure in the top stage to be intensified.

### **\*\*\* CONCLUSIONS**

The full potential of longwall mining was not realized until powered roof supports, particularly shield support systems, were developed. The stability of the shield permitted the application of longwall mining in conditions where caving was difficult to control and where chock and frame supports were inadequate.

Shield capacities continue to increase as a "bigger the better" philosophy prevails in longwall mining throughout the world. Several 900 to 1,000 ton shield systems are now in operation in U.S. coal mines. Several models have been developed based on theoretical and empirical support and strata interactions to determine shield capacity requirements. However, it is difficult to justify the current capacities strictly in terms of ground control requirements. Increasing the life expectancy of the shield has become a driving factor in current shield design and capacity considerations.

The increase in shield capacity has resulted in higher setting forces. Historically, mine operators have welcomed the higher setting force capability under the premise that it will help to strengthen the immediate roof beam by increasing the frictional restraint between bedded layers and provide additional active horizontal loading to provide further confinement to the face-to-waste strata movements that lead to roof falls in front of the shields. However, rock mechanics theory and limited underground shield loading data suggest that there is an optimum setting pressure and state-of-the-art high capacity shields may have exceeded this for weaker roof conditions. More research needs to be conducted to determine optimum setting pressures for high capacity longwall shields in order to provide the most effective ground control in various mine geologies while maximizing the life of the shield.

An often overlooked consequence of the increase in shield capacity is an increase in shield **stiffness**. If there is a strata control benefit in using higher capacity shields, it **may** well be due to their increased stiffness more so than their increased **capacity**. By developing the supporting forces more quickly in relation to the face **convergence**, the stiffer shields may reduce separation of immediate strata **layers** and minimize movement of the rock along fracture planes that lead to **premature** roof failures. Conversely, when the face convergence is irresistible, as is the case with main roof loading and to some extent with thick, **very strong**, immediate roof structures, the increased shield stiffness will result in **higher** shield loading. Since the stiffer shields will use up their available **capacity** as a passive support in irresistible strata movements more quickly, they **will** be fully loaded to their yield capacity as frequently as the less stiff, lower **capacity** shields they have replaced. In this scenario, one should not expect an improvement in the life expectancy of the high capacity shield over that of the previous **generation** of supports. This provides further justification for optimizing the setting forces, since the final support load will largely be dependent on the setting loading.

Laboratory performance testing of shields can be critical to a successful new shield design and invaluable in assessing the life expectancy of aging shields relative to their continued safe operation. NIOSH has recently opened its Safety Structures Testing facility at the Pittsburgh Research Laboratory for shield performance testing, providing unique capabilities using the Mine Roof Simulator (MRS) load frame. The MRS is an active load frame that more accurately simulates the in-service load conditions than static load frames. The MRS provides realistic and cost effective shield evaluation by combining both vertical and horizontal (racking) loading into a single load cycle. In addition to these advantages, NIOSH acts as an independent research organization to provide an unbiased assessment of shield performance.

Several of the current longwall shields have been in operation for a period of 7 to 10 years resulting in excess of 50,000 loading cycles. During the 1980's the life expectancy of shield was between 35,000 and 40,000 cycles. Today most manufacturers warranty their shields for a period of 5 years, which will cover about 25,000 cycles on an average longwall face. For a well-designed shield, the most likely structural condition that forces a retirement decision is excessive wear in the joints that connect the various component together. The manufacturing design tolerance is generally around 2.5 mm. The shield manufacturers typically recommend that the joints be rebuilt when an additional 2 to 3 mm of joint wear occurs. Excessive joint wear reduces dramatically the horizontal stiffness of the shield since the joint freedom must be overcome before the caving shield - lemniscate assembly participates in resisting face-to-waste strata movements.

Hydraulic problems will likely be encountered during the life of every longwall shield, requiring the leg cylinders to be rebuilt. Since leakage in any of the hydraulic components will result in the exponential decay of pressure with time to **zero**, meaning the support will have **no** load carrying capability after a certain

amount of time, these hydraulic problems should be identified and corrected as soon as possible. Observations of the relative positions of the cylinder staging can be used to identify cylinder problems and the cause of hydraulic leakages. A matrix of stage movements associated with each component failure was outlined in the report to assist mine operators in identifying and diagnosing shield hydraulic problems.

Unanticipated structural failures are most often related to fatigue failures, which act like a time bomb waiting to explode; there is little and often no warning that they are about to happen. Factors that lead to premature shield failure include: (1) poor quality control, (2) inadequate performance testing, (3) numerical modeling design errors, (4) corrosion. Failures of the base and canopy structure, tend to be the most prevalent.

### \*\*\* REFERENCES

1. Peele, R. Mining Engineering Handbook, Third Edition, John Wiley and Sons Inc. Copyright 1941, Vol. 1, pp. 10-5-5 to 10-5-11.
2. Mason, R. H. The First Longwalls Were Primitive Compared to the Ones Now in Use. Coal Mining and Processing. December 1976, pp. 59-64.
3. Wilson, A. H. Support Load Requirements on Longwall Faces. The Mining Engineer, 1975, pp. 479 - 491.
4. Peng, S. S., J. Wu, H. C. Li, and L. S. Shen. How to Select the Proper Type of Support. Colliery Guardian, February 1987.
5. Smart, B. G. D. The Evaluation of Powered Support Performance from Geological and Mining Practice Information". Proceedings 27 th U.S. Rock Mechanics Symposium, Alabama, 1986, pp. 367 - 377.
6. Peng, S. S., S. M. Hsiung, and Y. M. Jiang. Method of Determining the Rational Load Capacity of Shield Supports at Longwall Faces. Mining Engineer, October 1987, pp. 161 - 167.
7. Mukherjee, S. N. and L. Sudhakar. Estimation of Caving and Support In Longwall Faces.
8. Heasley, K. A. A New Laminated Overburden Model For Coal Mine Design. Proceedings on New Technology for Ground Control in Retreat Mining, NIOSH Information Circular 9446, 1997, pp. 60 - 73.
9. Longwall Census - US Longwalls Thrive. Coal Age, February 1998, pp. 22 - 27.
10. Adam, R. A., T. M. Barczak, and Irresberger. Strata Dynamics in Underground Coal Mines, Longwall USA, Pittsburgh PA, June 1991.

11. Hart, M. W. Longwall Production, Maintenance, and Roof Control System. Thirteenth International Conference on Ground Control In Mining, August 1994, pp. 136 - 147.
12. Graham, M. Longwall Mining Systems Evolve" Coal Age, March 1998, pp. 42 - 46.
13. Barczak, T. M. Practical Considerations in Longwall Support Selection. Ninth International Conference on Ground Control in Mining, Morgantown WV, June 1990.
14. Barczak, T. M. Selection of the Right Shield Support. Coal Mining, June 1990, pp. 63 - 67.
15. Barczak, T. M. and D. E. Schwemmer. Stiffness Characteristics of Longwall Shields. USBM RI 9154, 1988, 14 pp.
16. Barczak, T. M. and D. C. Oyler. A Model of Shield - Strata Interaction and Its Impact on Active Shield Setting Requirements. Tenth International Conference on Ground Control in Mining, Morgantown WV, June 1991.
17. Smart, B.G.D., P. W. H. Olden, and K. Metcalfe. Consideration of the Lateral Forces Generated by Powered Supports. The Mining Engineer, January 1992, pp. 189 - 196.
18. Barczak, T. M. and D. F. Gearhart. Shield Evaluation and Performance Testing at the USBM's Strategic Structures Testing Laboratory Published in Proceedings for Longwall USA, June 1996.
19. Coal Industry Annual. DOE/EIA-0584(96), November 1997, p. 29.
20. Barczak, T. M. Safety Evaluations of Longwall Roof Supports. USBM IC 9221, 1989, 17 pp.
21. Barczak, T. M. and D. F. Gearhart. Performance and Safety Considerations of Hydraulic Roof Support Systems. Seventeenth International Conference on Ground Control in Mining, Morgantown WV, August 1998.

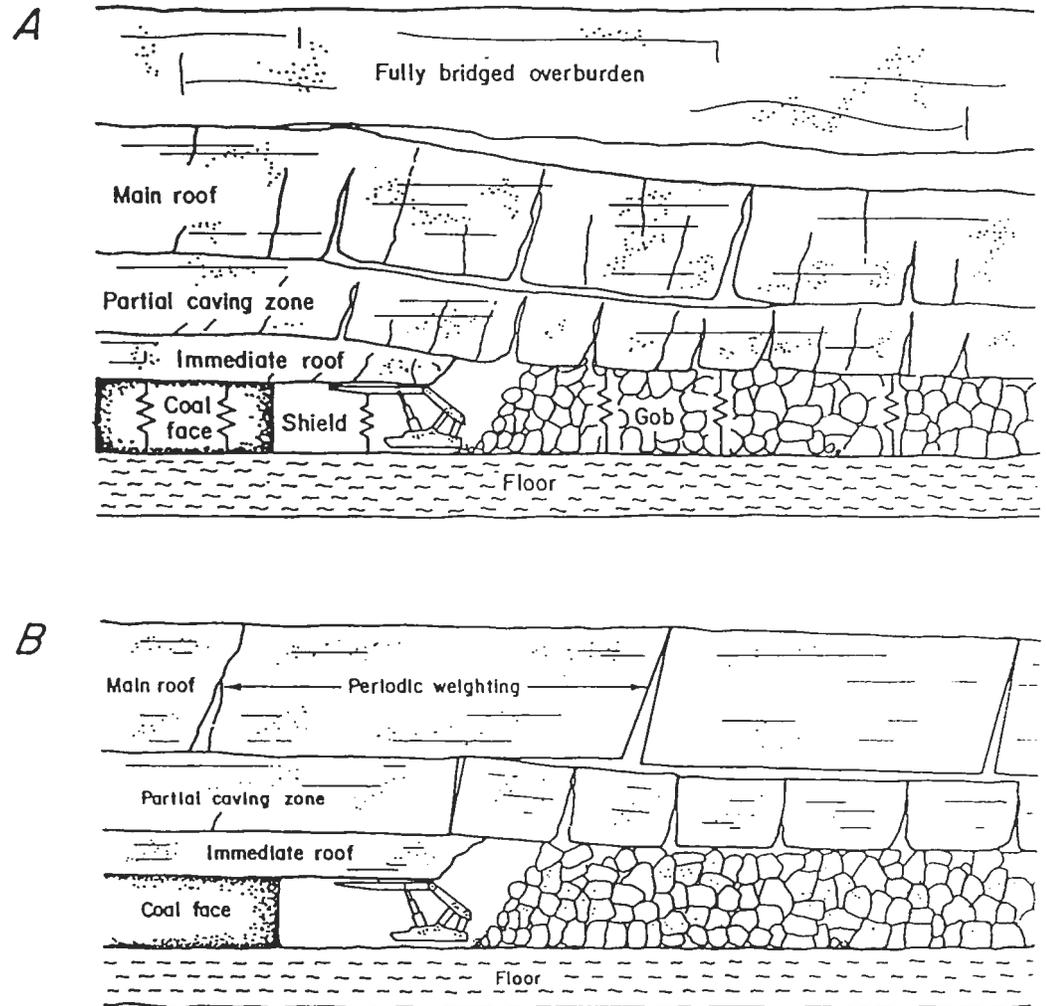


Figure 1. - Types of strata behavior that impact shield loading: (A) main roof deformation; (B) periodic weighting;

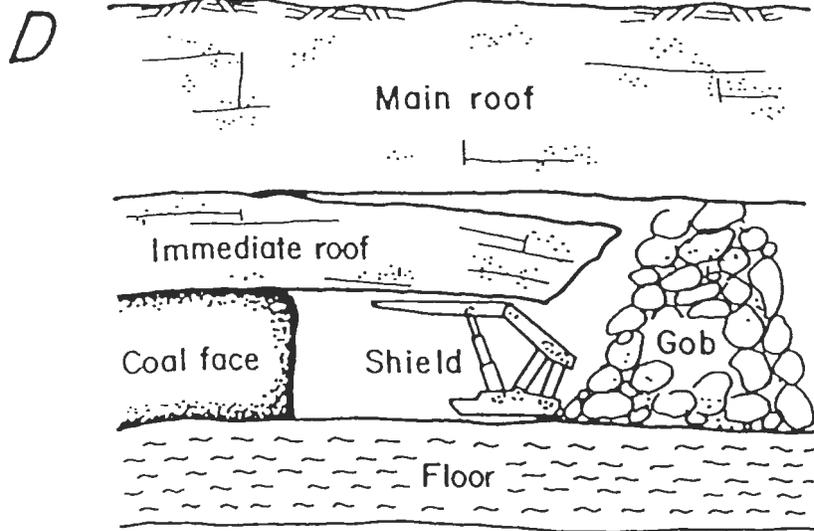
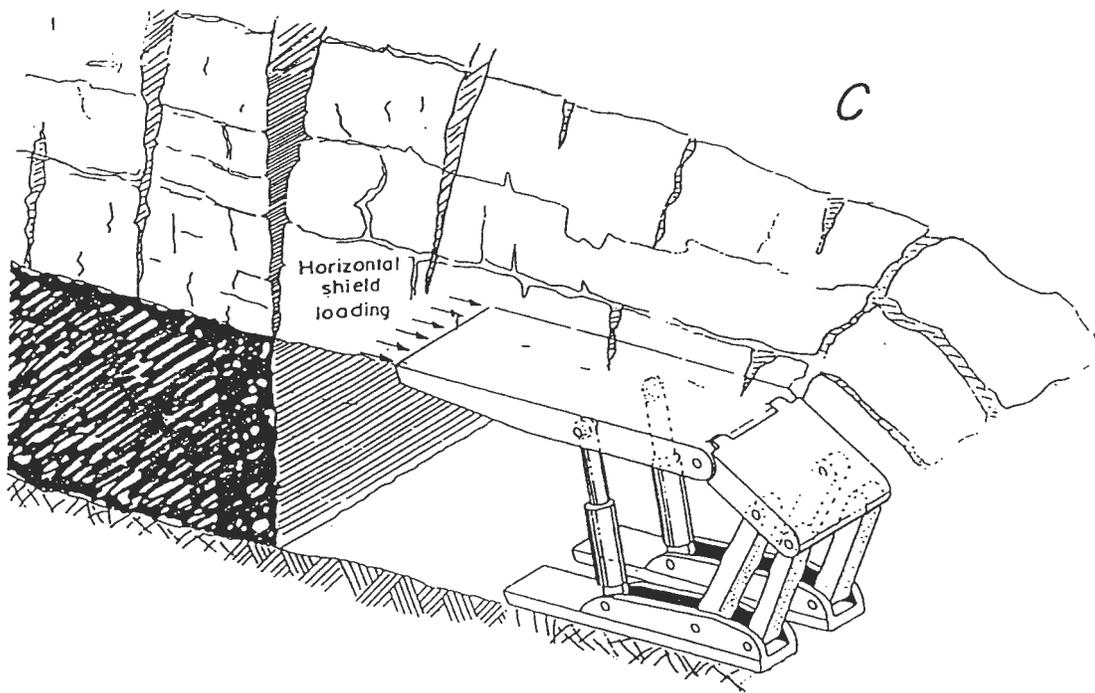
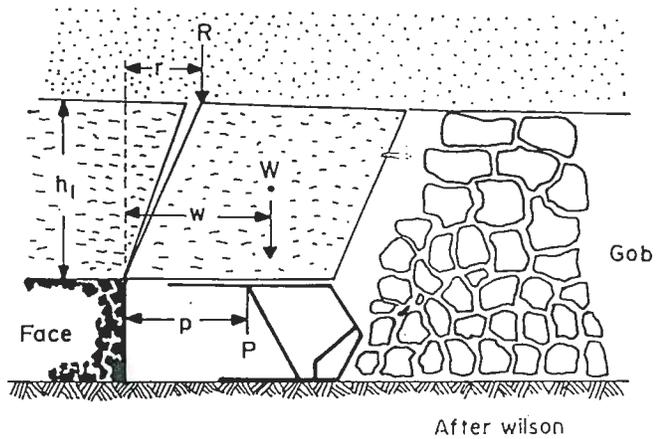


Figure 1 - Types of strata behavior that impact shield loading: (C) face-to-waste roof movement; and (D) deflection of the immediate roof beam.



Equilibrium requirements

Force equilibrium

$$W + R = P$$

Moment equilibrium

$$W(w) + R(r) = P(p)$$

$W$  = Weight of rock mass

$P$  = Resultant support resistance

$R$  = Reaction force to maintain moment equilibrium

Figure 2. - Shield capacity requirements based on detached roof block loading.

**Assumptions: (1) 20 DEGREE LEG ANGLE; (2) SUPPORT WIDTH- 1.75 m; (3) cave angle at rear of support of 30 degrees; (4) 20-ft long rock mass**

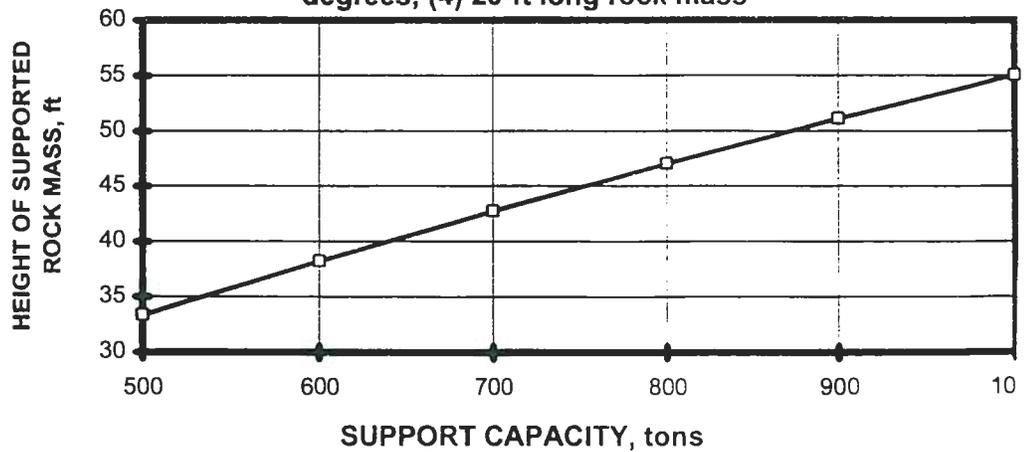
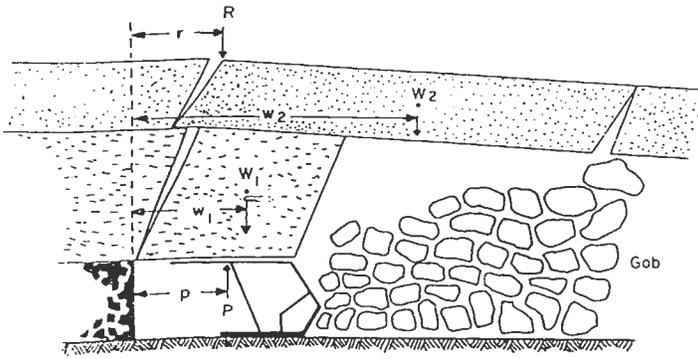


Figure 3. - Maximum caving height that can be supported by designated shield capacities.



Equilibrium requirements

Force equilibrium

$$W_1 + W_2 + R = P$$

Moment equilibrium

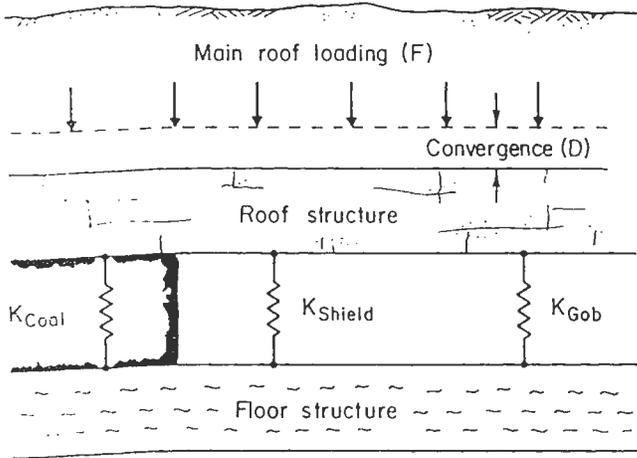
$$W_1(w_1) + W_2(w_2) + R(r) = P$$

$W_{1,2}$  = Weight of rock mass

P = Resultant support resistance

R = Reaction force to maintain moment equilibrium

Figure 4. - Shield capacity requirements based on periodic roof weighting.



$$F_{\text{System}} = [K_{\text{System}}] * D_{\text{System}}$$

$$\text{Where } K_{\text{System}} = K_{\text{Coal}} + K_{\text{Shield}} + K_{\text{Gob}}$$

$$F_{\text{System}} = \text{roof loading}$$

$$D_{\text{System}} = \text{roof convergence}$$

Figure 5. - Concept for estimating shield loading based on the stiffness of the shield, coal, and gob foundations.

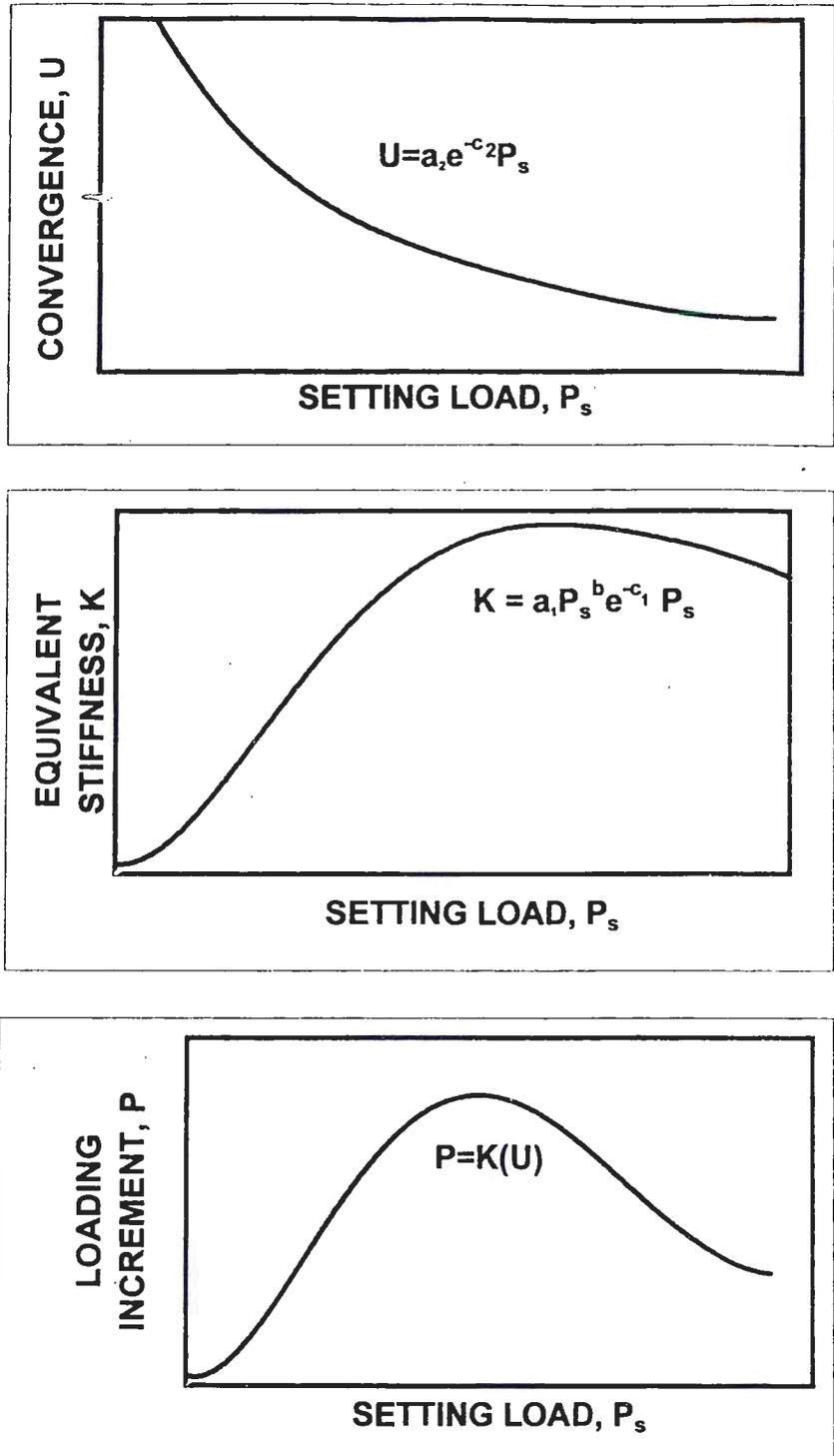


Figure 6. - Characteristic equations to evaluate shield loading based on equivalent stiffness of the shield and surrounding strata and the shield setting load.

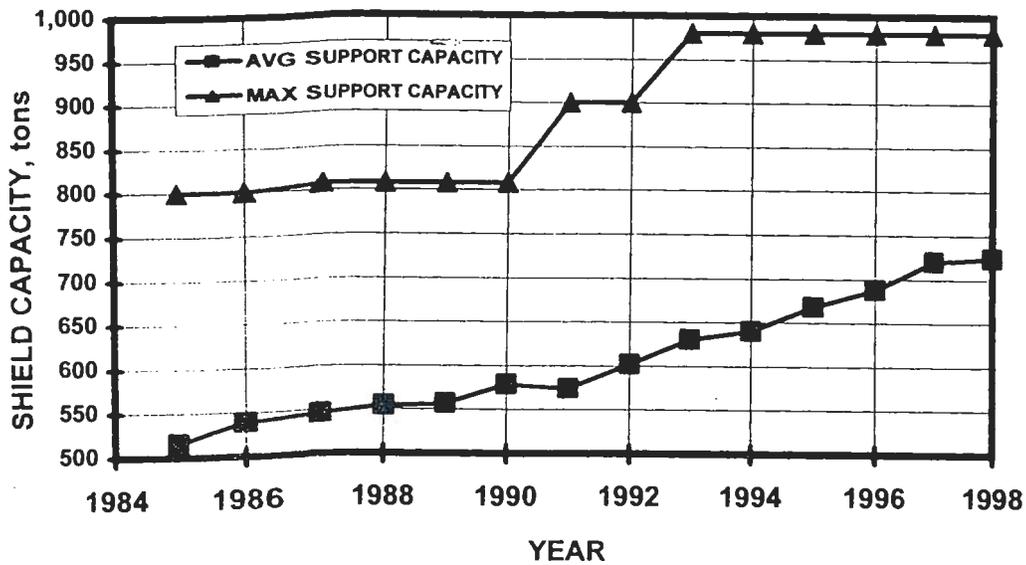


Figure 7. - Trends in shield capacity showing average and maximum shield loading.

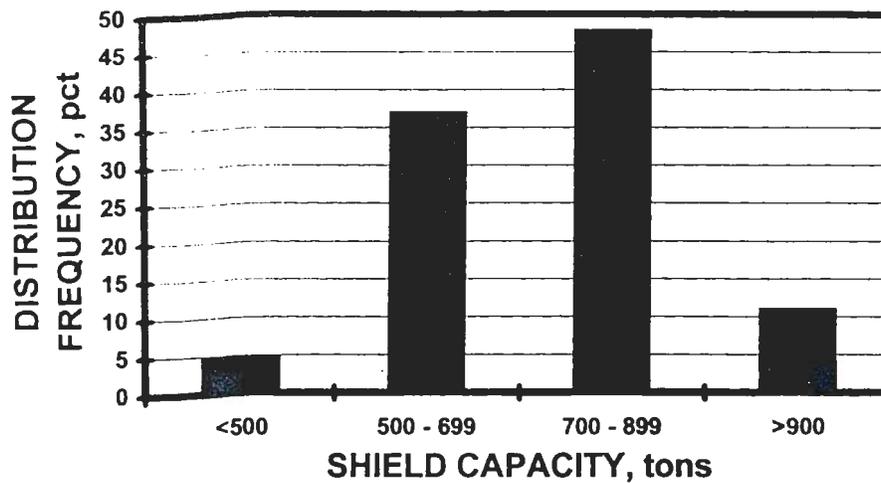


Figure 8. - Current distribution of shield capacities.

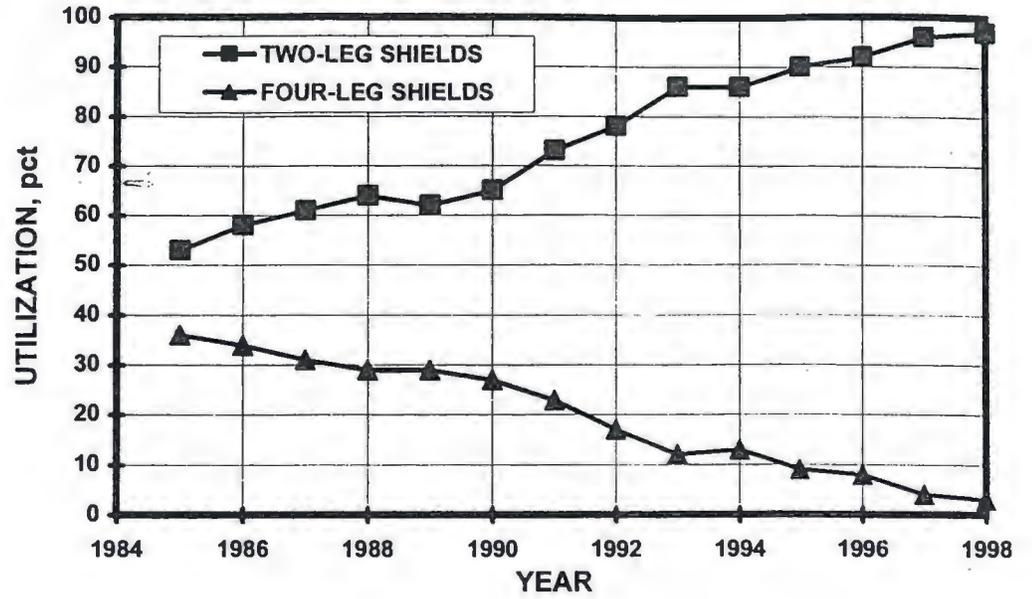


Figure 9. - Trend in the use of two-leg and four-leg shield designs.

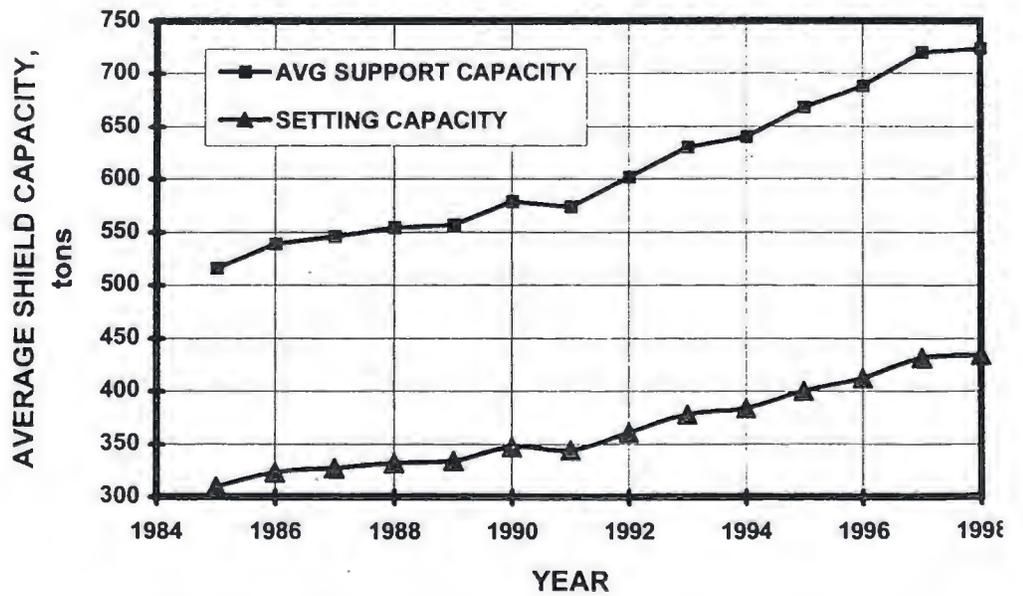


Figure 10. - Trend showing the proportional increase in setting loads as shield capacities have increased.

# ELECTROHYDRAULIC CONTROL SYSTEM

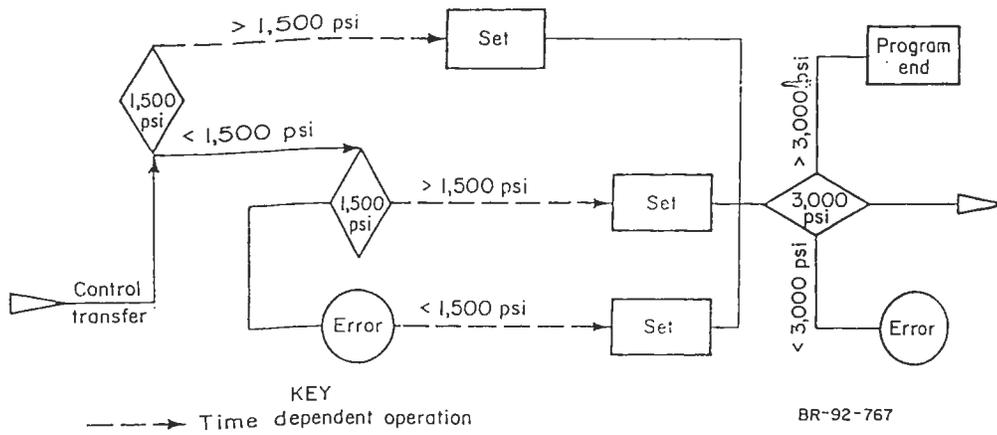


Figure 11. - Time dependent electro-hydraulic shield control algorithm.

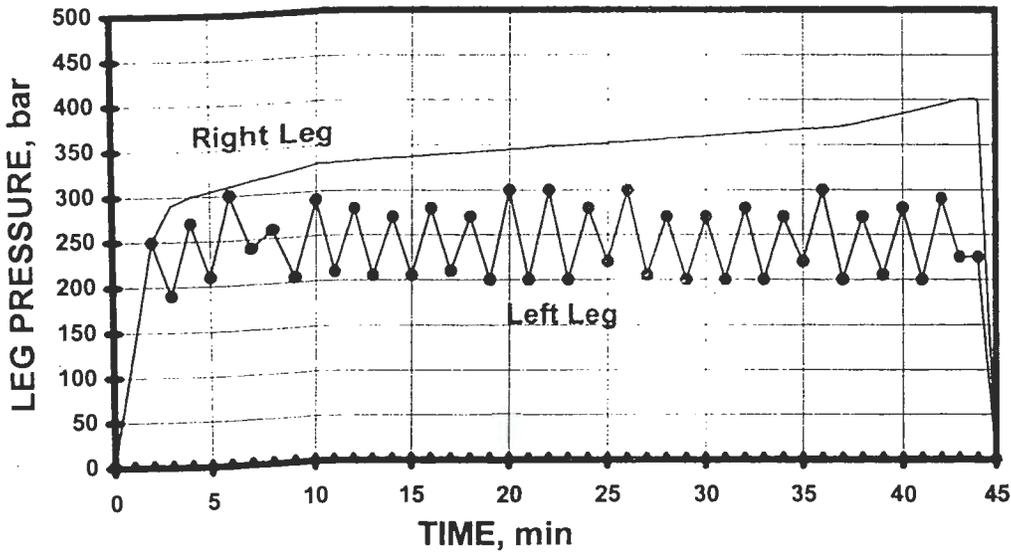
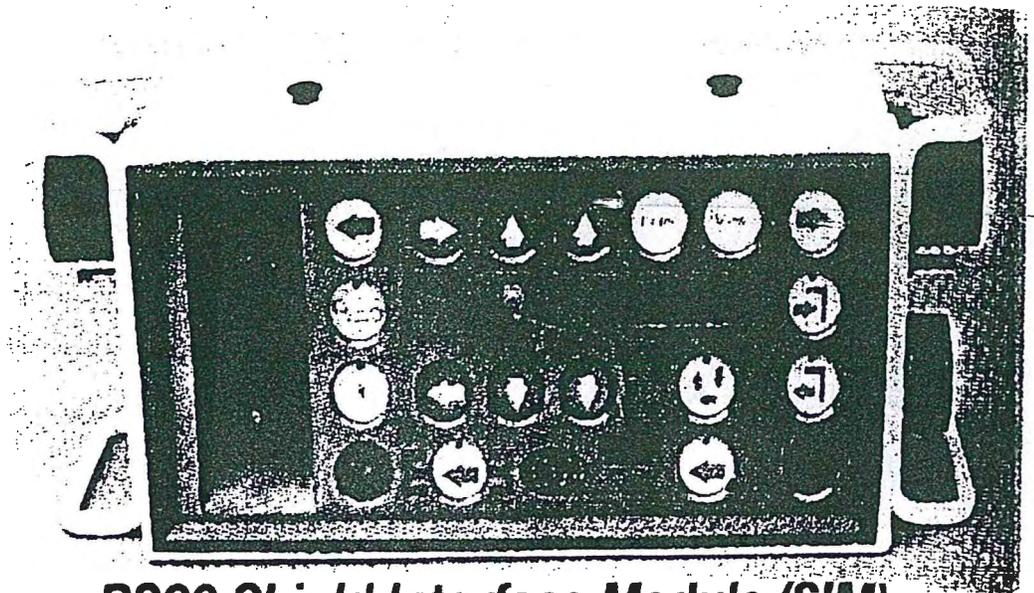


Figure 12. - Resetting of shield leg due to positive setting control algorithm.



**RS20 Shield Interface Module (SIM).**

Figure 13. - Electro-hydraulic control unit on modern longwall shield manufactured by Joy Mining Machinery.

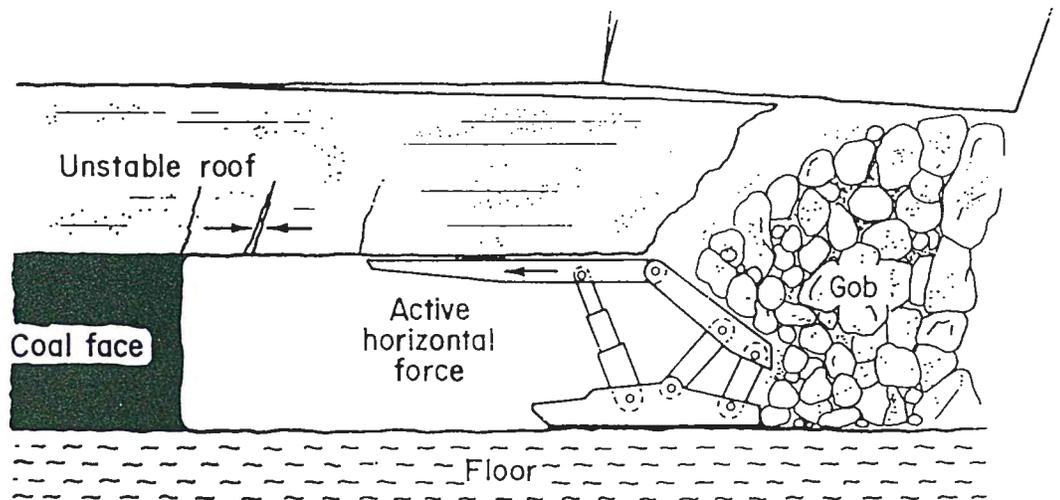


Figure 14. - Active horizontal loading capability of two-leg shield design.

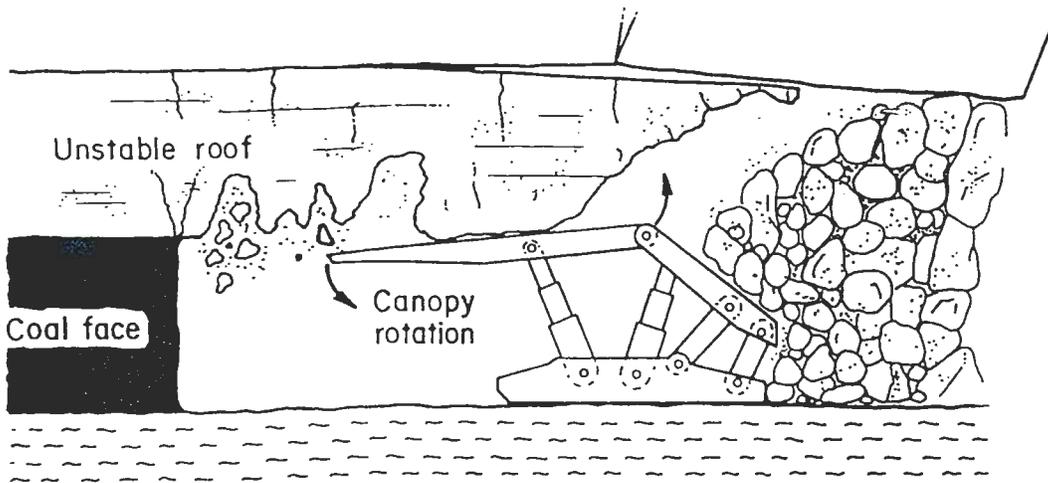


Figure 15. - Four-leg shield behavior in cavity prone strata conditions.

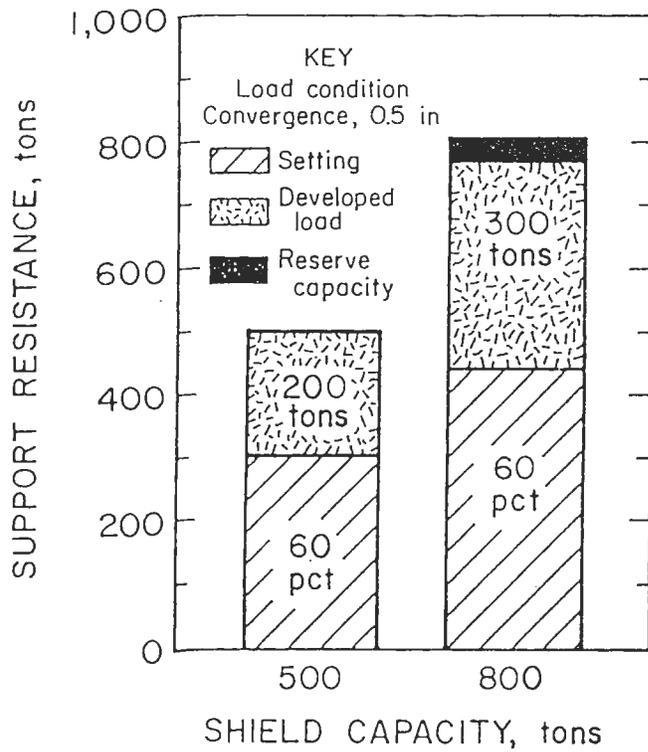


Figure 16. - Comparison of load development for 500-ton and 800-ton shield for the same load condition (0.5 inches of roof movement).

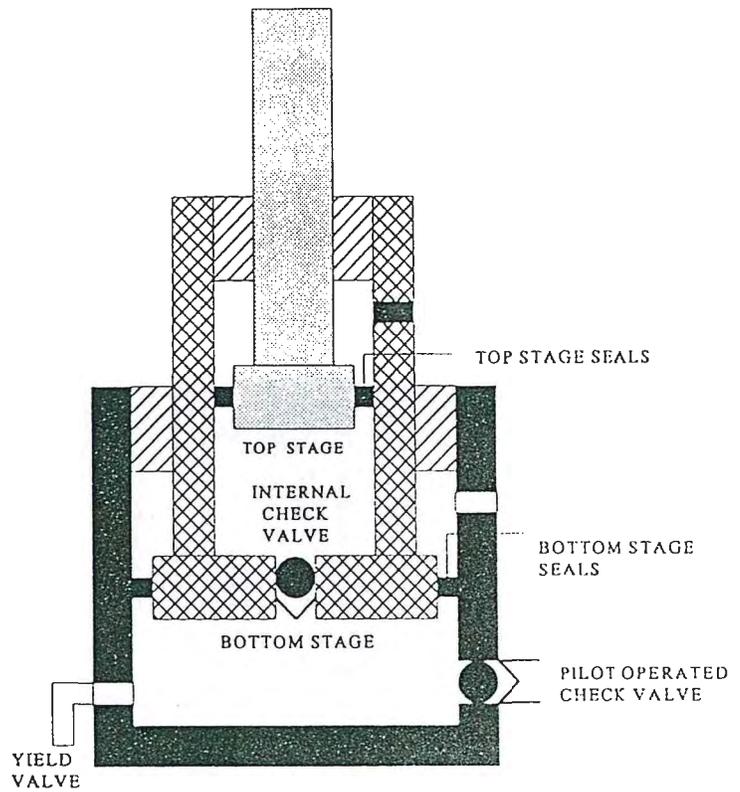


Figure 17. - Multi-stage leg cylinder design used in all shield supports employed in the United States.

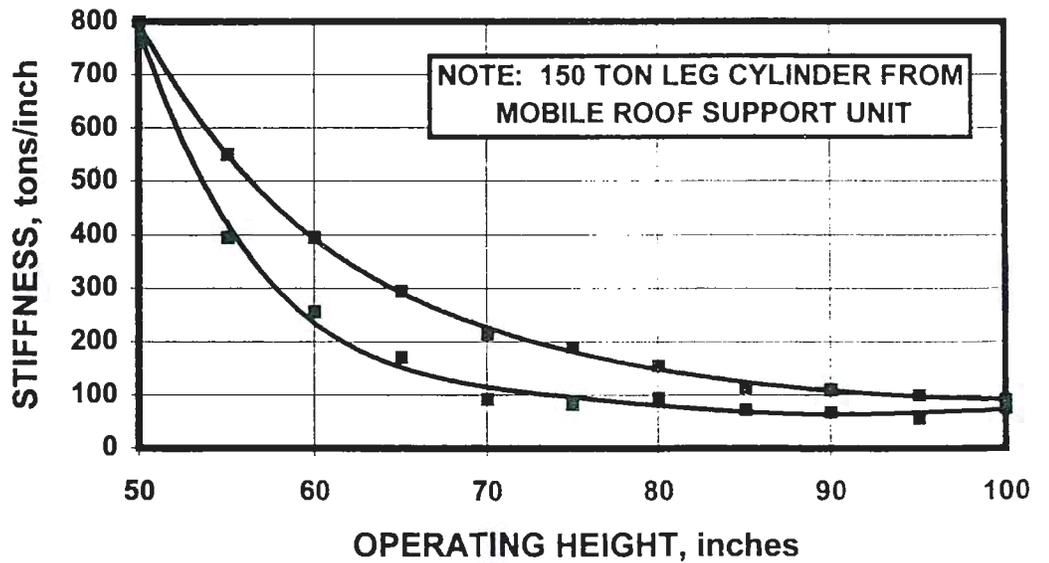


Figure 18. - Shield stiffness is a function of operating height and stage extensions.

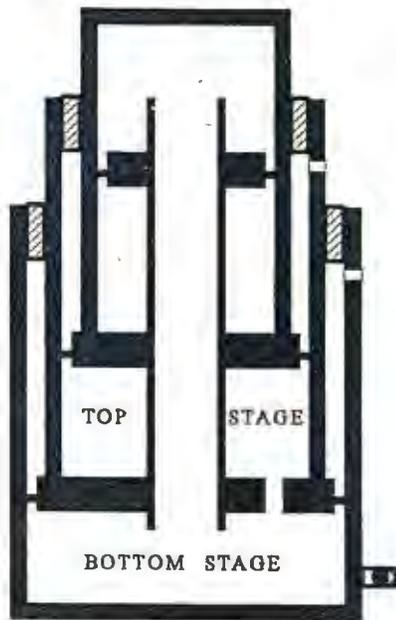


Figure 19 - (Fazos) Constant set leg cylinder design that provides full setting capability at all stage extensions.

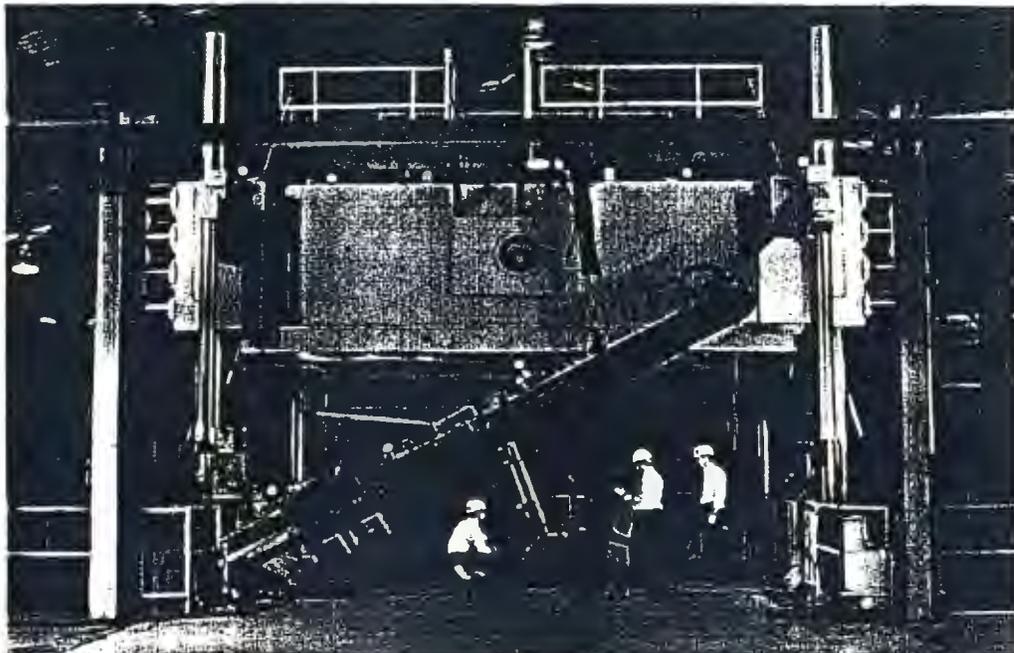


Figure 20. - Unique NIOSH Mine Roof Simulator load in the Safety Structures Testing facility at the Pittsburgh Research Laboratory.

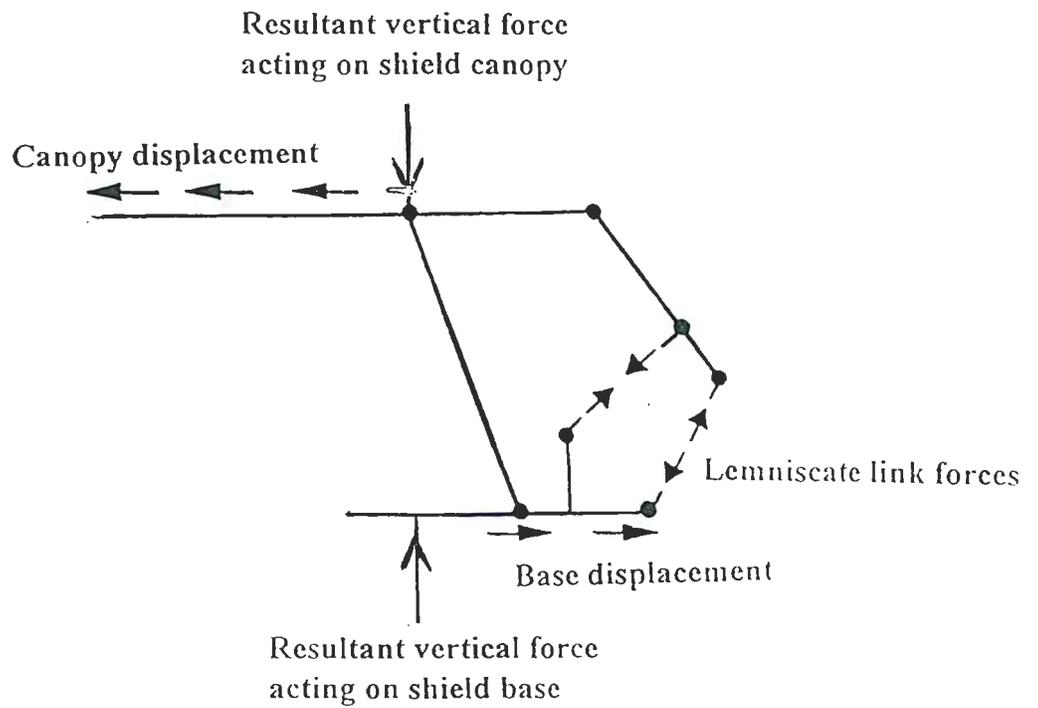


Figure 21 - Applied displacement and associate shield response for test series that eliminates horizontal loading acting on shield in order to maximize lemniscate link and base toe loading.

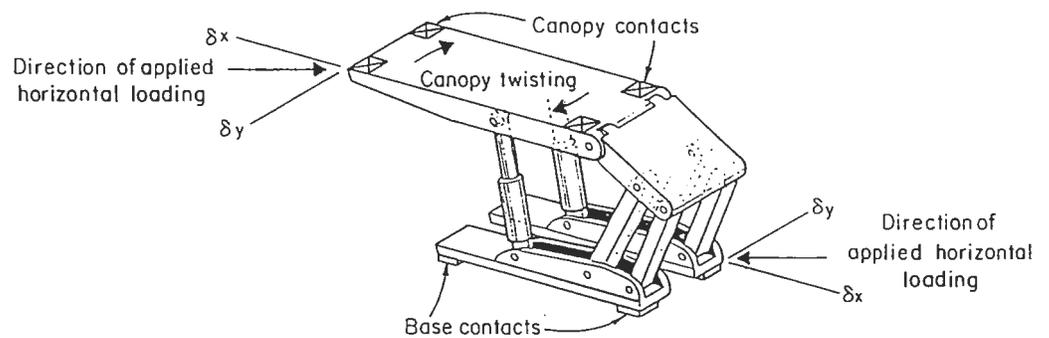


Figure 22. - Eccentric face-to-waste horizontal loading to maximize loading in the various shield joints.

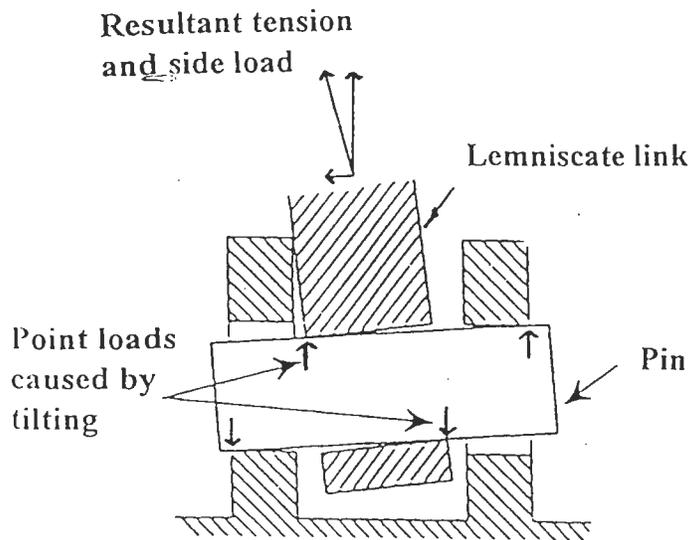


Figure 23. - Point loading in lemniscate link joints due to eccentric horizontal shield loading.

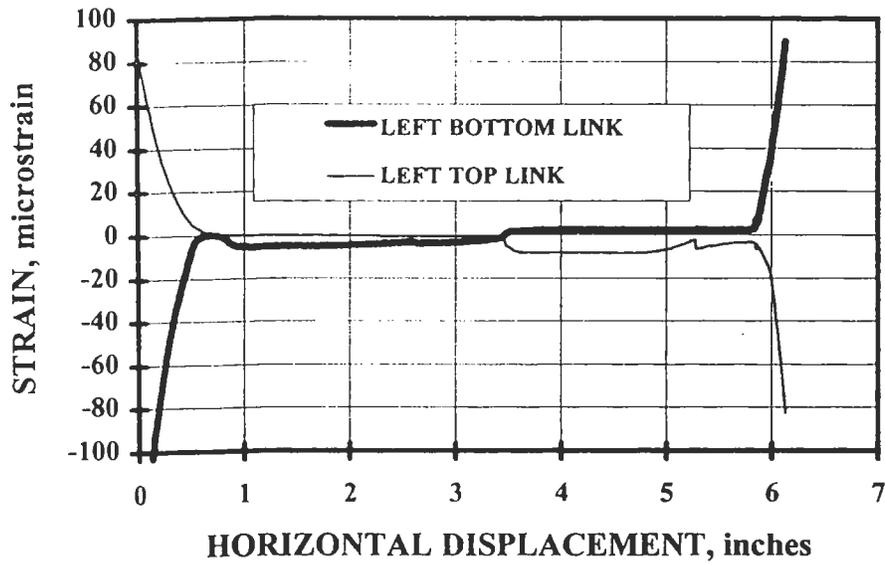


Figure 24. - Five inches of horizontal displacement required to overcome translational freedom in worn shield joints.

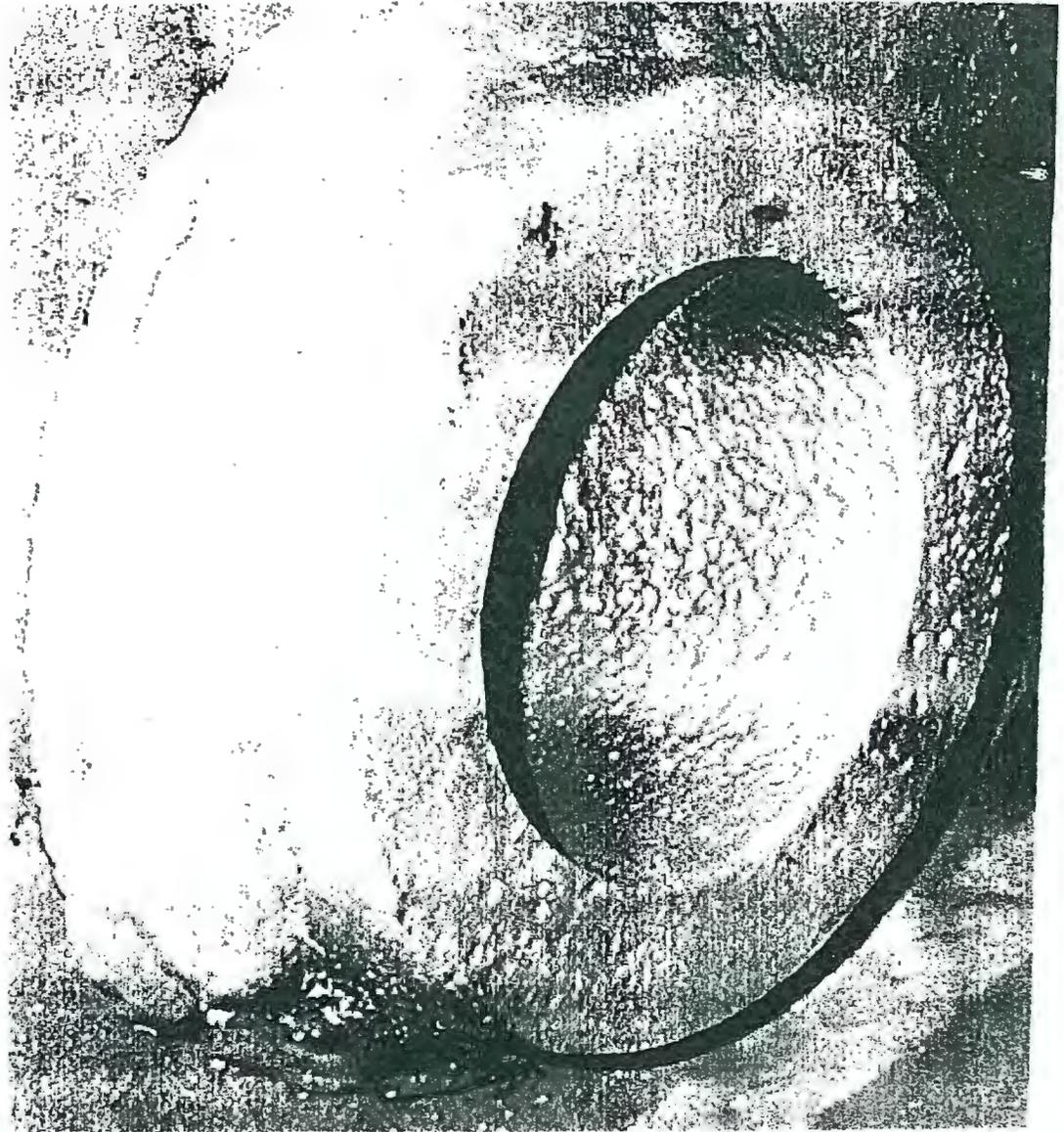


Figure 25. - Pits in lemniscate link bores due to corrosion.

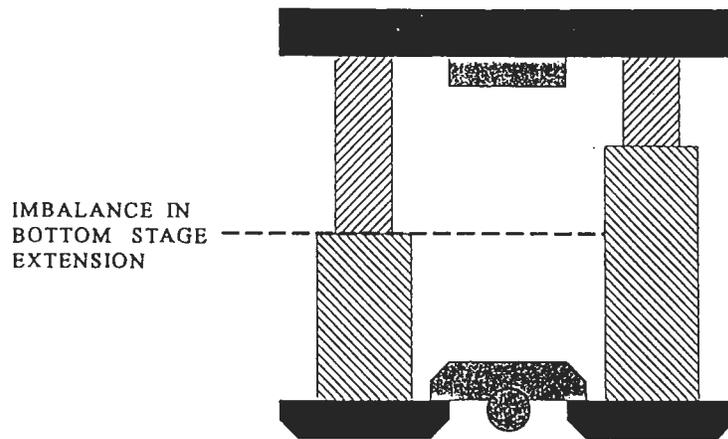


Figure 26. - Difference in bottom stage extensions on hydraulic cylinders is an indication of internal leakages that can reduce support capacity.

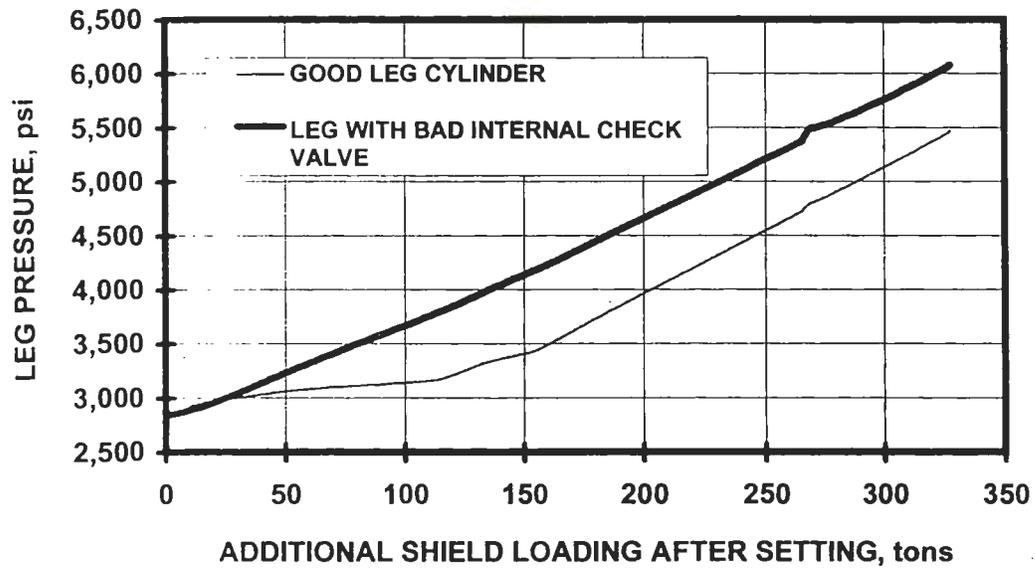


Figure 27. - Bad internal (staging) check valve can be detected by leg pressure responses when the bottom stage is fully extended.

# **LONGWALL USA**

INTERNATIONAL EXHIBITION & CONFERENCE

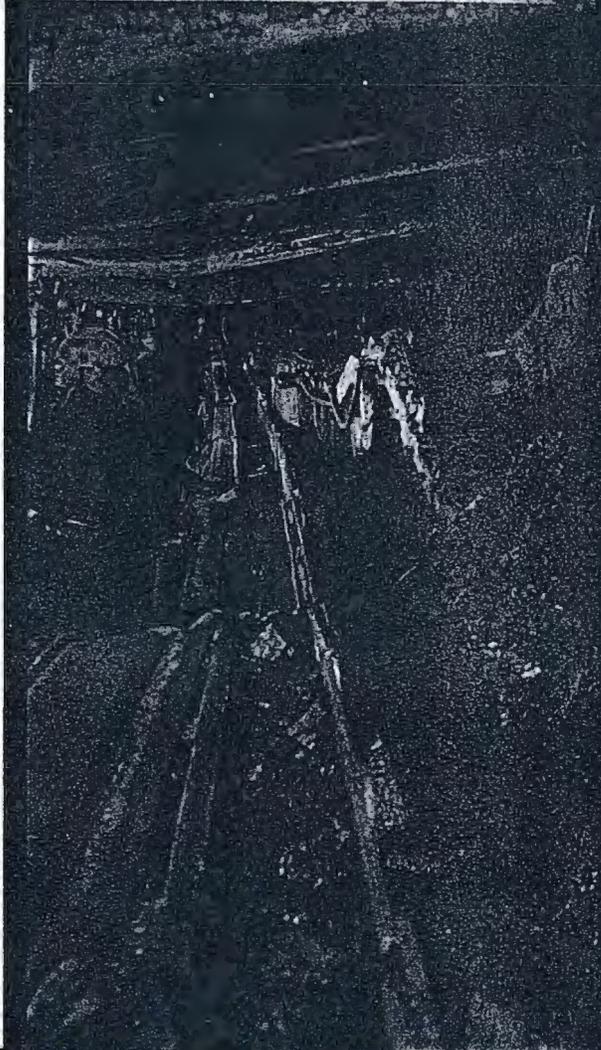
JUNE 9 -11, 1998

DAVID L. LAWRENCE

CONVENTION CENTER

PITTSBURGH, PA

**The Only  
Specialized  
Exhibition and  
Conference for  
Longwall Mining**



## **PROCEEDINGS**

\$40 U.S.

SPONSORED BY

# **Coal Age**