DESIGN CONSIDERATIONS FOR THE NEXT GENERATION OF LONGWALL SHIELDS

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ABSTRACT

Advancements in support technology have occurred to a large extent because of the demands of the mine operators. Shield supports are no exception. The most notable changes in shield technology in the past decade have been increases in shield capacity and life expectancy, which have increased by a factor of 4 and 7 respectively since the inception of the shield support 25 years ago. The purpose of this paper is to set goals for the future generations of longwall shields. These goals include: (1) 100,000 cycle life expectancy, (2) improved hydraulic diagnostic capability, (3) smart load control with adjustable setting pressure algorithms, (4) composite material design to reduce weight and increase shield width, (5) constant set leg cylinder design, (6) improved joint design to reduce wear and stress, (7) advancements in leg cylinder socket design, and (8) an instrumented shield to measure in-service structural component loading. These design issues will continue to push the envelope in longwall shield technology that has provided the safest and most productive mining system employed in the history of mining. In preparation for this, a historical examination of shield failures is made and recent trends in shield design are evaluated. Design practices to improve structural margins of current designs are also addressed.

INTRODUCTION

Reviewing the 25 year history of the use of the shield support for longwall mining in the United States, it is clear that the shield had a major role in making longwall mining the most productive and safest mining method available to U.S. operators. The basic shield structure has remained unchanged for the past 25 years, although the structures have grown dramatically in size and capacity. Early generations of shields experienced several structurally related failures and had to be strengthened to prevent premature failures and provide a reasonable working life. Through this evolution of improvements, the life expectancy has been increased by a factor of 7 from 10,000 loading cycles in the late 1970's to 70,000 loading cycles today. Apart from technological improvements in electro-hydraulic control systems, which have impacted the operational capability of the support, there have been relatively few advances in shield design in the past 10 years.

The purpose of this paper is to revisit shield technology and to propose some considerations for further enhancements in shield design. The scope of these ideas include both short terms solutions that can be accomplished with current technology as well as bigger goals that may require some additional research. Nonetheless, these concepts can provide for a new generation of shields, which will last longer, provide more intelligent use of the available support capacity, and improve structural margins of safety to ensure that premature failures do not occur.

Reviewing the design history of longwall shields, it is apparent that the U.S. operators have had a major impact on the design improvements that have occurred. Dating back to the initial longwall installations, where the integrity and capacity of the European shields were not up to the standards, the U.S. operators insisted on higher capacity and more reliable structural performance, and then continued to demand greater working life as the shields evolved, the U.S. mine operators are clearly the motivating force behind the improvements that have been made in the past. It is just as likely that any future improvements in shield design, such as those proposed in this paper, are more likely to occur if the U.S. operators push for them.

RECENT TRENDS IN SHIELD DESIGN

Material Specifications – Shields in recent years have been fabricated from high strength steels (100,000+ psi yield) to minimize component cross sectional dimensions. High strength steel applications were first used in canopy structures to minimize the cross sectional thickness of the canopy in low to moderate seam applications. Today, high strength steel in all shield designs is necessary to provide the required strength for various shield components in high capacity designs. While the added strength has helped to extend shield life, the high strength fabrications are more susceptible to brittle failure and catastrophic fatigue failures. Another consequence of some high strength steel applications is that special welding practices are required (heat control, etc.) making underground repairs more difficult.

Capacity – Support capacity has continued to increase throughout the history of longwall mining. This trend for the past 15 years is shown in figure 1 (Coal Age, 1999). Average support capacities in the United States have increased by nearly 50 pct since 1985 to an average support capacity at yield of 768 tons for the 62 operating longwalls in the U.S. in 1999. Twelve installations (19 pct) of the current longwalls employ shields with capacities greater than 900 tons, and 19 installations (50 pct) have capacities between 700 and 900 tons. The current distribution of shield capacities is shown in figure 2. The highest capacity shield used in the United States is 1,170 tons (Coal Age, 1999). As shown in figure 1, maximum shield capacities have evolved from 800-ton shields which were common from 1985 to 1990 to the current 1,200-ton shields 1999.

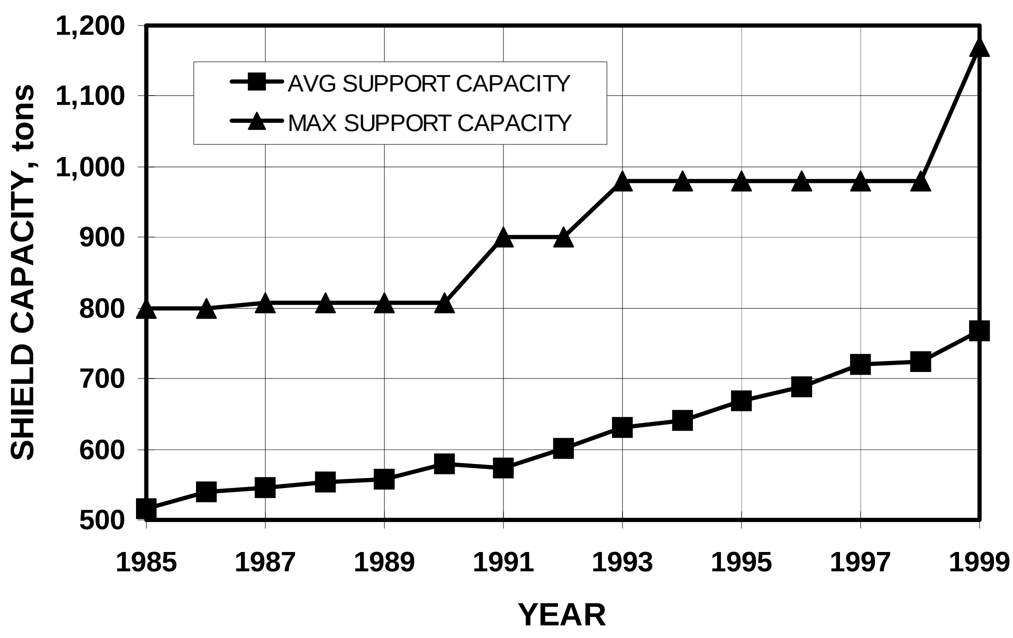

Figure 1 Trend showing increase in support capacity

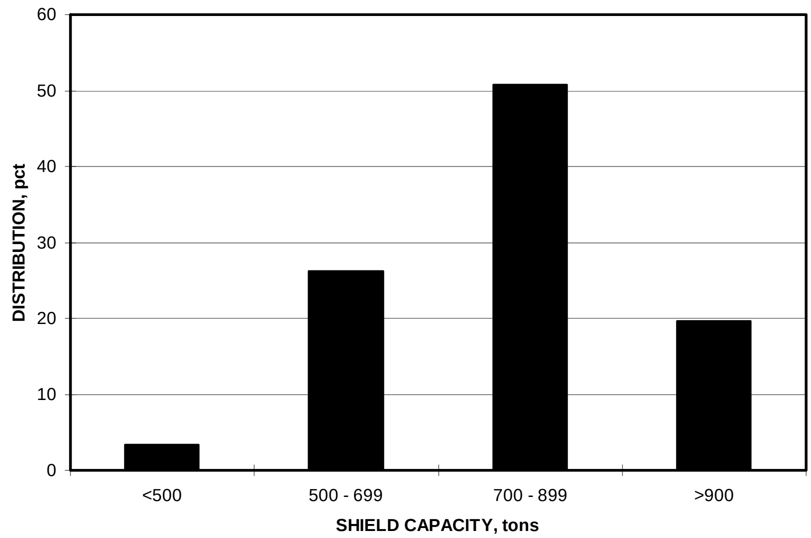

Figure 2 Distribution of capacity for shield operating in 1999

The increase in capacity has significantly impacted shield design and ground control capability. In order to provide the increased support capacity, larger diameter leg cylinders had to be utilized. One consequence of the larger diameter leg cylinders has been a proportional increase in shield stiffness. The increase in shield stiffness means that the load developed in the support structure will occur at less displacement or face convergence. While the increased stiffness may provide superior control of the immediate roof, main roof weighting that causes irresistible (in terms of the shield capacity) convergence on the longwall face will result in greater shield loading with the stiffer shield design. As a result, it is not uncommon for the high capacity shields to be fully loaded to yield capacity just as often as lower capacity designs that they replaced. An example is illustrated in figure 3 where a 500, 800, and 1,000-ton shield are all fully loaded when 0.5 inches of convergence occurs.

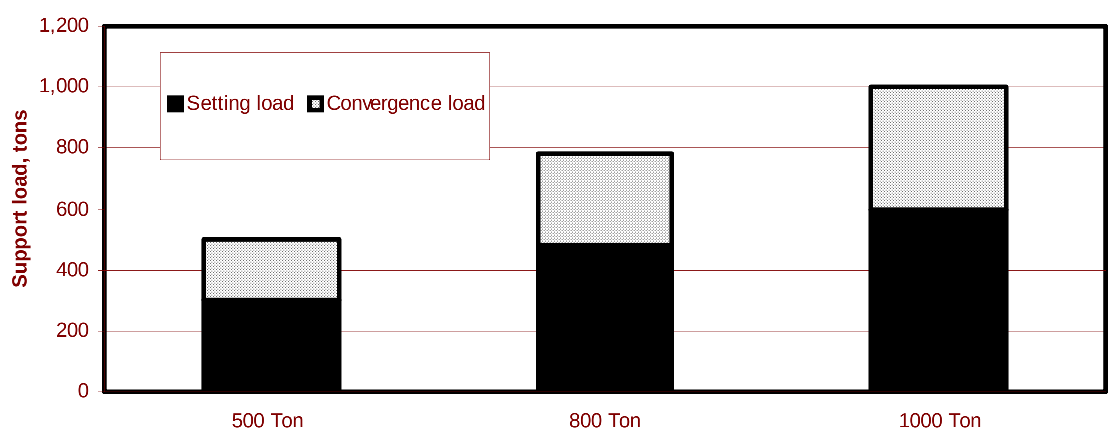

Figure 3 Setting load and load developed due to roof movement for shields of various capacity

Another consequence of the larger diameter leg cylinders is that the leg socket must be designed to accept greater loads. Historically the leg socket has been a source for premature shield failures and the increased loading makes the design even more demanding. In addition, the larger diameter leg cylinders require a wider and longer socket, which places further demands on the design of the socket and load transfer to the base and canopy structures. In general, the larger diameter cylinders have resulted in wider support components which are more susceptible to torsion loading than before.
Several models have been developed over the years to determine support capacity requirements. 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. 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 have controlled recent developments in longwall shield design and capacity determinations.

***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, and two-leg shields are becoming the favored support worldwide. 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.

There are several consequences of the two-leg design. From a support strata interaction perspective, the two-leg shield provides an active horizontal force toward the coal face due to inclination of the leg cylinders. This active horizontal force improves overall strata stability by arresting slippage along fracture planes or by prevention the expansion of highly jointed or friable immediate roof geologies which may be further damaged by the front abutment loading. In terms of the shield loading, this increase in active horizontal loading also translates into proportionally higher lemniscate link loading. Historically, lemniscate link pins and wear in bores has been a primary cause of premature shield retirement and/or rebuild. Hence, pin diameters and bore areas need to be increased in higher capacity shields to prevent this problem from becoming worse.

Another issue related to the two-leg concept is 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 800 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. There has also been a trend toward solid base designs to reduce floor-bearing pressures in two-leg shields.

***Size* –** In addition to wider shields required by larger diameter leg cylinders, there is a trend toward wider shields to minimize hydraulic cylinder maintenance and reduce the total cost by employing less leg cylinders on a longwall face. Again the issue of torsion is important in designing wider shields. It is not as easy as simply extending the width of the canopy and base. These components also need to be strengthened for torsional loading. There is also the issue of weight. The 2.0 m wide designs may represent an upper limit with current shield construction materials. If high capacity designs are to prevail, then lighter weight materials such as composites are likely to be needed to develop widths much beyond 2.0 meters.

In addition to increases in width, shields have increased in length to accommodate one-web-back operations and larger face conveyors and deeper shearer webs. Longer canopies and bases create much larger bending moments that require stiffer and stronger components than in previous generation supports. The increase in length is largely responsible for the need for greater shield capacity as the area of roof loading carried by the shield increases or the greater convergence is seen by the cantilevering of the immediate roof beam as the resultant shield force moves further from the coal face.

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. This design practice coupled with the increased stiffness of the higher capacity supports means that the higher capacity shields are fully loaded as often as their lower capacity predecessors (figure 3).

Hydraulic Components and Control Systems **–** Both manufacturers continue to make improvements in the electro-hydraulic control systems, making them more reliable, more user-friendly, and easier to diagnose when problems do occur. A description of these systems can be found in a paper entitled “Shield Design, Construction, and Operation” published in the proceedings of Longwall USA (Barczak et al., 1998). 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.

SUMMARY OF FAILURES EXPERIENCED BY MINE OPERATORS

There have been numerous shield failures throughout the history of the shield support. A summary of these is provided below. While failures have declined, particularly premature failures that occur early in the shield life, there are still isolated cases of premature failures. Shields have a finite life and fatigue failures will eventually occur on all shields if left in service long enough.

Historical Overview of Shield Failures

Base Failures - Base failures seem to be the most prevalent and usually occur from fatigue after the support has been in operation for several panels of extraction. A common failure mechanism is for the leg socket casting to break away from the base structure. Formation of this failure is difficult to detect while the support is in-service, as the leg socket is housed deep inside the base structure and this area usually is full of debris. Once the leg socket breaks loose, the support quickly becomes inoperable. The bottom plates of the base have insufficient strength to withstand the leg forces and the leg cylinder will literally rip the base apart by tearing off the bottom plate.

Failure of the base structure (plates) can also occur without the leg sockets failing. The probable failure mechanism is bending of the base. This is more likely to occur in mine sites which have very strong immediate floor strata. In these hard floor conditions, steps in the floor may be left by the shearer as it is difficult to maintain a constant height of extraction from cut to cut. The base structure is then simply supported in two locations and is flexed as loading is applied. Repeated flexure causes the base to deform (plastically) or promotes fracture from fatigue which eventually results in failure of the base structure. In softer floor conditions, the strata deforms to provide a fuller contact to the base. This alleviates much of the bending and reduces the risk of failure. Standing the support on the toe of the base can also result in damage of the base structure. This configuration causes maximum stresses in the toe region and the base will deform or fail usually where the cross section is a minimum in the section of the base forward of the leg connection.
Internally, the base structure is constructed with stiffeners which hold the top and bottom plates apart to form a beam arrangement which gives the base its bending strength. Cases have been reported where these stiffeners have not been properly welded in place or where the dimensional tolerances were not within specifications. In these cases, the stiffeners broke loose and the base structures literally collapsed. This problem appears to be largely a matter of quality control, but it

is critical to support safety. Since the stiffeners are hidden inside the base structure, it is virtually impossible (excluding X-ray inspection) to see these deficiencies prior to the failure.

Canopy Failures - Canopy structures are constructed of stiffened (top and bottom) plates similar to base structures, and hence they are susceptible to bending-induced failures as well. Structurally, canopies are less stiff than bases making them more susceptible to failure from bending than base structures. However, while permanent deformation of the canopy is a fairly common occurrence, destructions of canopies appear to be less frequent than observed destructions of bases. This suggests that canopies are less often subjected to critical bending. Three reasons why canopies might avoid critical loading are: (1) immediate roof strata is usually partially fractured and full contact with the canopy is more easily obtained which minimizes bending moment; (2) tip loading on the canopy is usually smaller than toe loading on the base, since the resultant force is more likely to be located near the toe of the base than the near the tip of the canopy; and (3) the canopy surface area is larger than the base area which allows the canopy to distribute load more efficiently.

Another common deformation of the canopy is "wrinkling" of the top plate between the internal stiffeners. This is due probably to concentrated loading at locations between the stiffeners, but might also be an indication of failure of the weldments that hold the stiffeners in place. If the stiffeners are not secure, the plate may buckle from excessive stress that results in bending of the plate between the more rigid stiffeners.

Caving Shield And Links - Link members have become considerably more robust in shield designs during the past ten years, and failures have been substantially reduced. Since the caving shield-link assembly has very little vertical load capacity (stiffness), links are not highly stressed for most load conditions. Almost all link failures can be attributed to conditions or operating practices which promote standing the support on the toe of the base or conditions which cause large horizontal displacement of the canopy relative to the base.

Failure of the structure is most likely to occur in the region near the (pin) hole located on each end of the member. The failure mechanism is most likely crack formation somewhere on the circumference of the hole from localized high stress development. The holes elongate from continued wear and contact with the higher strength link pins. This results in point loading of the pins and high stress development at the contact areas. These failures are difficult to detect since this area is obscured from view by the caving shield clevises or base structures. Although link failures are rare, they can be catastrophic as the links provide horizontal stability to the support structure.

Likewise, caving shield failures are fairly rare, but are more likely to occur than link failures. While links are designed primarily for axial loading only, shield mechanics indicate the primary loading mechanism for the caving shield is bending and torsion. Maximum stresses and failure are most likely to occur in the clevis areas where pins connect the link members to the caving shield. Some general yielding by bending deformation of the caving shield structure may also occur.

***Leg Cylinders* -** Assuming the face area is sufficiently stable to prevent violent outbursts of energy (bumps), it is unlikely that leg cylinders will experience structural failure since they are designed to control loading by hydraulically yielding at specified pressures. The most common failure associated with leg cylinders is seal leakage.

Another potential failure mechanism for hydraulic leg cylinders is for the yield valves to malfunction, allowing leg pressure to increase beyond design levels. Usually, the excessive pressure will cause seal leakage, so that it is unlikely that sufficient pressure will build up to rupture the cylinder casing. The more common problem is leakage through the yield valve which causes unplanned pressure losses during normal loading. This leakage can be caused by dirt or contamination not allowing the valve to seat properly or worn seats, defective springs that maintain the valve in the closed position, or the fitting itself may leak due to bad O-rings or seals.

FAILURE ASSESSMENT OF SHIELDS CURRENTLY IN SERVICE

The age distribution of the shields operating in 1999 is shown in figure 4. The range of operating life extends from 0 to 14 years of service. An average shield operates about 4,000 cycles per year, translating into a face production of approximately 2.5 million tons per year. Hence, an average 10-year-old shield would have 40,000 loading cycles, while a shield employed on a high production longwall (4 million tons per year) would have about 65,000 loading cycles. Approximately one third of the shields have been in operation from 4 to 6 years (16,000 - 24,000 cycles), and slightly more that than one-third (37%) have been operating for more than 6 years (24,000 loading cycles).

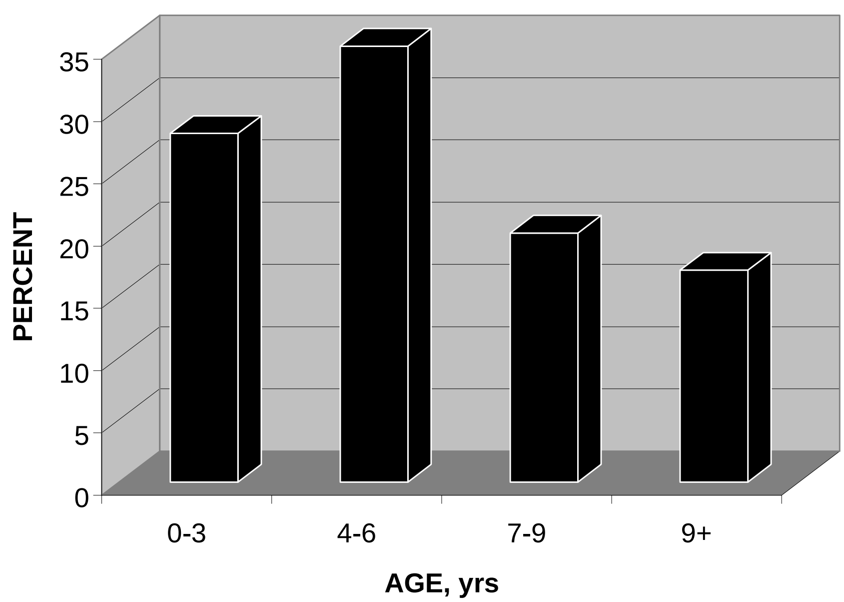

Figure 4 Age distribution of shields operating in 1999

Figure 5 shows a near-linear increase in structural failures with age. Failure is defined as structural damage to any support component. It does not necessarily mean catastrophic failure that renders the support inoperable. The linear relationship suggests that **there are more than just fatigue failures occurring**, since the frequency of fatigue failures should increase at a much greater rate as the shield ages. There was a wide range of structural failures reported. Most of the major failures involved either the leg sockets or pin joint problems (i.e., lemniscate link pins and clevises). These two failures are most likely to put a shield out of service and/or require structural modification to keep the support in service. Other structural failures occurred at areas of high stress concentration including the side shield on the canopy structure, the canopy capsule tilt cylinder bracket, the base bridge, the link cut out areas in the caving shield, various mounting brackets including the pilot-operated/yield valve manifold, and dishing of canopy skin covering plate. There were a few isolated cases of leg cylinder casing problems, but no catastrophic failures.

There were **more hydraulic problems reported than structural problems** (figure 5), particularly in shields that have been in operation less than 6 years. There were nearly 4 times the number of hydraulic failures in shields operating 3 years or less and nearly twice as many for shields in the 4 - 6 year range than there were structural failures for the same age group. Obviously, the weak link in shield design is the hydraulic system. Numerous hydraulic failures or problems were reported. The high frequency of failures in the first 3 years of operation is distorted by failure of a component called a hydrafuse. The hydrafuse is a safety device incorporated by Joy as part of the leg cylinder design on their recent generation of shield supports in response to a fatality that occurred recently in Australia. An Australian mineworker was killed when the hydraulic fluid in the retract annulus of the leg cylinders was inadvertently pressurized while setting the support. Normally, the retract port is open through the return line back to the hydraulic reservoir whenever the leg cylinder is being pressurized. This is necessary since the pressure would be highly intensified (by a factor 30 or more) if the port was blocked, as in the case of the Australian fatality. The resulting pressure intensification caused the cylinder end cap to rupture, striking and causing a fatal injury to the mineworker.

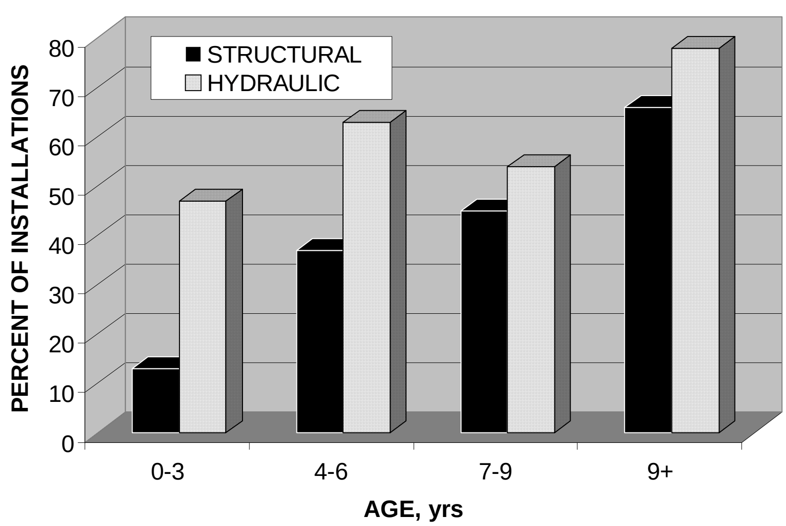

Figure 5 Distribution of structural and hydraulic failures on shields as a function of age

The hydrafuse is incorporated into the retract circuit and acts as a yield valve to prevent the inadvertent build-up of pressure in the retract annulus of the leg cylinder. The design utilized by Joy features a brass clip that shears off at a predetermined load (hydraulic pressure). Once the clip is broken the “fuse” must be replaced. With a failure pressure of nearly twice the pump operating pressure, it was expected that the fuse would provide the desired safety on the rare occasions when there was abnormal pressure, and that replacement of the hydrafuse after the failure would not be much of an inconvenience. To the surprise of most everyone, hydrafuse failures began occurring on several shields at several mines. The failures seemed to occur whenever the support had set idle for a period of time, and whenever the leg pressure was at or near yield pressure and almost always on the top stage retract circuit. However, it is believed that a water-hammer effect is being created by the valve operation. Joy has since installed a restricter valve in the circuit to dampen out any potential pressure spike. Early indications from the field installations indicate that this may be working to prevent the undesirable failure of the hydrafuses. Unfortunately, the restrictor also increases the time required to lower the top stage. Fortunately, in two-stage leg cylinder designs, the bottom stage is lowered first and lowering of the top stage is only required when the bottom stage is fully collapsed (Barczak, 1998). Hence, the increased time to lower the top stage will not be a problem during most production mining.

Other cylinder problems caused pressure losses that limited support capacity. One example was due to poor fabrication where the internal bore of the top stage was off center resulting in a weakened casing that was unable to sustain the pressure intensification that occurred in the top stage. Other problems were reported with defective yield valves that would not reset resulting in the inability of the shield to adequately hold load after yielding. Similar problems were reported with the staging valve which also caused loss of pressure in the leg cylinders at a few mines. One mine reported clearance problems with the leg cylinder and the base rib plates where the cylinder leaned into the rib plates causing internal damage to the cylinder and seal leakage. Failures also occurred with the advance ram cylinders including failure of shuttle valve springs and structural failure of a hollow tube relay bar design.

Most hydraulic problems are related to internal leakage due to seal wear and/or corrosion of the cylinders. These problems typically begin when shields have been in service 4-6 yrs. As figure 5 shows, 60 pct of the shields had some sort of hydraulic problems during this time frame. Many problems go undetected for extended periods of time, resulting in degraded support capacity that can contribute to ground control problems in heavy loading conditions. Methods to detect the onset of internal hydraulic leakages are discussed later in the paper. As previously described, there is a trend towards the use of low treatment synthetic fluids in western mines. One western mine reported severe leg cylinder corrosion due to problems with a low treatment synthetic emulsion on shields that have been in operation less than 3 years.

Problems with the electro-hydraulic control systems were also reported. These included sticking solenoid valves (problem with soaping in emulsion formulation) and chattering valves due to fluid dynamics at high flows. Most mines reported that there have been significant improvements made in the latest generation of electro-hydraulic controls. In particular, the DBT (MTA) PM-4 system seems to be a significant improvement over the previous generation PM-3 design.

Design Practices That Improve Structural Margins of Safety and Extend Shield Life

Since most structural shield failures can be attributed to some form of fracture, the basic elements of fracture control can significantly improve shield life. These are: (1) use a lower design stress, (2) minimize stress concentrations, (3) reduce flaw size or control crack growth, (4) minimize corrosion, and (5) use materials of improved toughness (Barczak, 2000).

Lower Design Stress - Some margin of safety should be employed in the design stress relative to the yield strength of the steel. Civil engineers typically use a factor of 1.66, meaning that the allowable stress is about 60 pct of the yield stress for non-fatigue loading and further reduced by 50 pct or more when fatigue loading applies (AISC, 1980). While these levels of safety are not practical in shield design due primarily to cost and weight limitations, it is important to recognize that a small reduction in (tensile) stress developments will significantly reduce crack growth since the two are related by an exponential function. Past practices of designing to or near yield strength should be avoided in modern shield design where the life expectancy exceeds 50,000 loading cycles.

Link pins and clevises are a prime example of historically poor design practices in shield supports which continue even today. Deformation and/or excessive wear in the pin clevises are undoubtedly the primary cause of premature shield retirement and/or structural rebuild. There are clear indications that these areas are subjected to stress beyond the yield strength of the steel. This poor design is caused partly by manufacturers not giving sufficient credence to the load conditions which cause high loading in the caving shield - lemniscate assembly, namely loss of frictional contact at the roof and floor interface and standing the support on the toe of the base. With the possible exception of shields designed for low seam heights, there is adequate space available to increase the bearing area of these clevises and pin diameters to reduce the stress and substantially improve the life expectancy of these components. The joint design problem also needs to recognize the importance of pin tolerance. First, the pin contacts only a portion of the clevis. Typically, arcs of 45 to 60° are used in the design analysis. Obviously, the 45° arc assumption will lead to more conservative designs. Conservative assumptions should be made to allow for reduced areas as wear occurs (figure 6). Corrosion effects are also often ignored or not sufficiently accounted for in the design of pins, despite the fact that corrosion is a leading cause of premature pin failures or abnormal wear. Corrosion causes pits to occur in both the pins and the clevises (figure 7) which can reduce the bearing area by 25 to 50 pct and cause a proportional increase in stress.

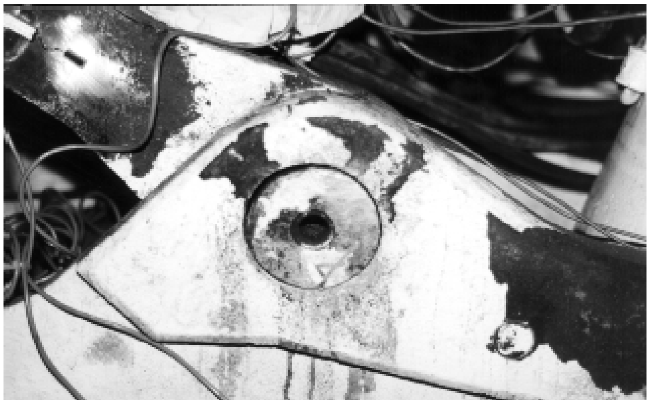

Figure 6 Reduction in lemniscate pin contact area for worn joint

Figure 7 Corrosion of a lemniscate link clevis

Several failures have occurred where the leg socket casting weldments break due to fatigue or stress-corrosion, and thereby cause subsequent failure of the bottom base plate as the loading is transferred fully to the bottom plate instead of being distributed to the side rib plates. Most of the time the leg cylinder and casting punch through the bottom plate and into the mine floor rendering the support inoperable. A common modification to alleviate base leg socket failures of this nature is to add another plate to the under side of the base pontoon. Typically, this plate is about 1 inch thick and usually covers most of the length of the base pontoon. Reinforcement is also typically added to the top area of the side base plate. While this plate stiffens the side plate, its primary purpose is to restore the location of the centroidal axis, which was changed by the addition of the bottom plate, to its location in the original base design. The stiffness of the base should be fully examined during the initial design phase of the shield in order to prevent these failures from occurring.

Some mines have successfully reduced operating stress levels by **derating the shield support** prior to underground installation. The derating is accomplished by installing yield valves with a lower operating pressure than specified in the design. Since the leg capacity controls the maximum load developments within the support, lower leg loads translates into reduced component loading. For example, if a 1,000-ton shield support is derated by 10 pct to a 900-ton capacity, the margin of safety relative to the tolerable crack size that will prevent fatigue fracture may increase by 20 to 30 pct.

Minimizing Stress Concentrations **-** There are numerous sources of stress concentrations in longwall shield supports. The most common is a change in geometry. These stress concentrations should be identified and their magnitudes quantified during the design and performance-testing phase. One way to do this is to use photo-elastic plastics. The photo-elastic plastic can be applied to almost any area of the shield structure. Colored fringes will appear on the plastic when observed through a polarized lens that correlates to the stress profiles. **Stress intensity factors of 2-3 are not uncommon** for sharp changes in geometry such as holes or sharp bends in structural members.

One example of a sharp change in geometry is a lemniscate link design with offset pinholes as shown in figure 8. This link design is typically employed on a shield with a low profile designed for operation in low coal seams. The bend is necessary to provide clearance with the caving shield in the collapsed or low operating height. Lemniscate links are primarily axially loaded members, but the offset pinhole geometry induces additional stresses due to bending, and thereby significantly reduces the margin of safety for this component. Figure 8 depicts failure of a bottom lemniscate link on a 620-ton Westfalia shield that occurred during performance testing at the NIOSH Safety Structures Testing Laboratory. Although the shield had 45,000 load cycles from underground service prior to the testing, a new link was installed on the shield that was performance tested in the laboratory. This was a new link design that was fabricated for the mine by an outside vendor (not the support manufacturer). Failure occurred after only 14,000 loading cycles. This failure illustrates two problems. First, the design (allowable stress) was too high. Test results revealed that the nominal stress in the link exceeded 90 pct of the material yield strength. In addition, it appeared that the link side plates had been torch cut, adding an additional stress riser to the already sharp change in geometry at the bend in the link in the area where the failure occurred. These two factors resulted in an unacceptable time to failure. Figure 9 illustrates another problem where the fabrication process left large flaws that led to premature fatigue failure of the base rib. This problem may have been alleviated if the surface was smoothed to remove most of the surface flaws.

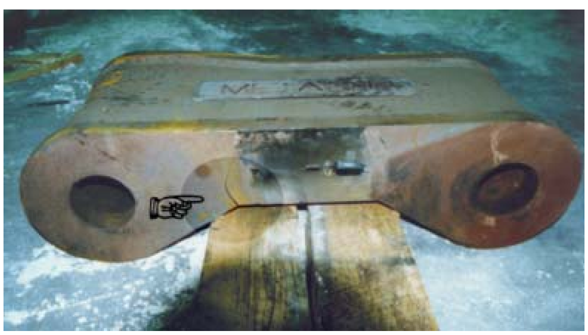

Figure 8 Failure of bottom lemniscate link

Figure 9 Failure of base rib side plate where fabrication process left large flaws

Any hole in a structural plate is another area where stress is concentrated. The structural components of a longwall shield (canopy, caving shield, lemniscate links, and base) are connected by a pin and clevis arrangement. These areas are also sources of stress concentration and fatigue failures on aging longwall shields (figure 10). Another example of a stress concentration caused by too sharp of a change in geometry is shown in figure 11. Holes are sometimes cut into the canopy or caving shield structure to accommodate the placement of hydraulic hoses. In the example shown in figure 11, failure occurred at the stress riser caused by the sharp corner in a cut-out on the caving shield made to accommodate hosing for the side shield. The best solution to this problem is to avoid the hole altogether, and if the hole is necessary, to make sure that the corner radius is as large as possible. Another example of failure due to stress risers created by sharp geometries is shown in figure 12, where a crack developed in the caving shield near the canopy hinge. A clean-out hole is often placed in the side of the base structure to facilitate removal of debris from the leg socket area. This too can be a source for concentration of stress. Since this is a critically loaded area of the base, care should be taken in the design to minimize the stress concentration by a incorporating a favorable geometry and orientation with respect to the stress field in this member.

Figure 10. Failure in base lemniscate link clevis

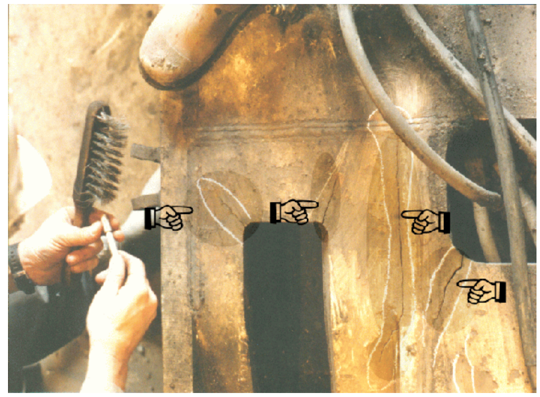

Figure 11 Failure due to stress concentrations in cut out sections of caving shield

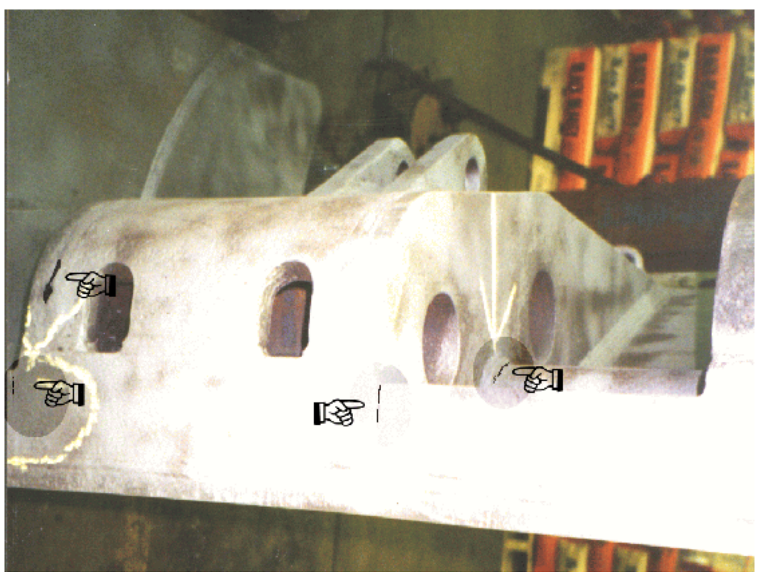

Figure 12 Failures of caving shield due to stress concentration in sharp corners where lemniscate links connect

Figure 13 shows failure of a canopy leg socket casting due to a stress riser created by a sharp change in geometry. The failure in this case occurred in the casting itself. This failure occurred on several shield supports in the late 1980's, all of which utilized this same basic socket design. Again, this failure probably could have been prevented by a smoother geometry. Leg sockets are often a source of fatigue failures in aging longwall shields. The leg socket is a critical area since the full load developed within the hydraulic leg cylinder must be transferred into the canopy and base structures to be distributed to the mine roof and floor. An examination of the structural mechanics associated with these base socket failures has led to some other design changes that are intended to reduce the stress concentration in the leg socket casting/base structure connection.

The rectangular geometry of the socket casting and its placement between the side rib plates of the base structure position it at right angles to the principal tensile stress caused by the bending of the base structure. This orientation creates a stress intensity factor which helps to promote fatigue-induced fracturing of the weldment. Some shields are now being designed with more of an elliptical or zipper-shaped casting (figure 14) so that the front and/or rear edge is not perpendicular to the principal tensile stress, thereby resulting in a reduction of the stress intensity factor.

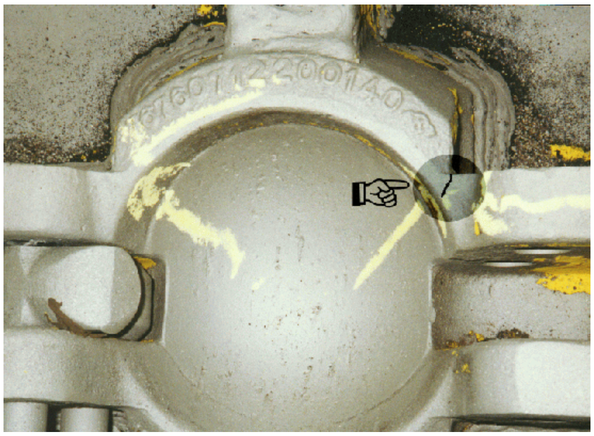

Figure 13 Failure due to stress riser created by sharp corner in canopy leg socket casting

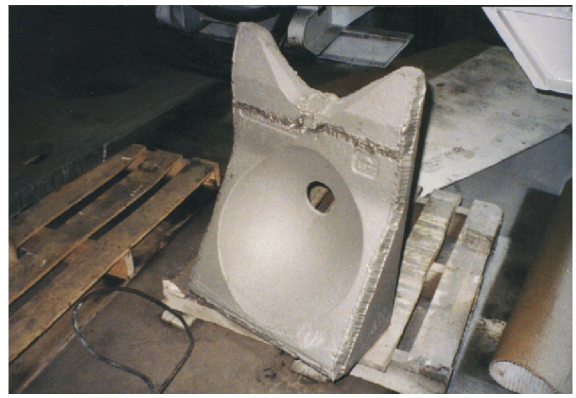

Fig. 14 "Zipper-shaped" leg cylinder casting to avoid stress concentration caused by orientation of casting to principal stress field

Reducing Flaw Size or Controlling Crack Growth **-** Weldments are an essential part of the shield fabrication process. However, since weldments are a primary source of structural flaws, the quality of the welds is critical. As the principles of fracture mechanics illustrate, the initial flaw size created by the welding process is critical to the crack propagation and the margin of safety achieved in this structure. Once a crack develops, it is desirable to keep the crack contained within the weld and not have it progress to the base material adjacent to the weld. This action may depend on the nature of the heat-affected zone in the immediate vicinity of the weld. In general, the heat affected zone results in anisotropic material properties and residual stresses that tend to reduce the toughness of the steel in this area and increase the likelihood of fracture into the base metal. For the high strengths steels used in modern shield supports, proper heating and cooling of the steel during the weldment process is crucial to preventing crack initiation and growth in the heat affected zone. This is why it is very difficult to conduct repairs to damaged shields underground, since it is virtually impossible to be able to preheat and properly cool the steel when welding at the longwall face. Another approach that can be used to keep crack growth contained to the weldments is to create breaks in the weldments. This practice is sometimes used in leg socket castings. The break in the weld at the corners of the casting acts like as a crack arrester to stop the growth of the crack. This same technique is used in the airplane industry by drilling holes in the metal at the end of an observed crack before it reaches a critical crack length.
Perhaps the best approach to avoid problems associated with weldments is to eliminate them when possible. A good example of this pertains to the leg socket design. A typical construction

for the leg cylinder base socket is shown in figure 15. A casting 3-4 inches thick and 18-24 inches long with a spherical seat to accommodate the bottom of the hydraulic cylinder is placed on top of the bottom cover plate on the base pontoon, and is welded in place along the four sides of the top of the casting to the side rib plates and cross plates that connect the two side base plates together. This design is highly dependent on the welds to transfer load into the side rib plates and maintain the structural integrity of the socket connection. An alternative design that is now being employed in some canopy leg sockets to alleviate the weld fatigue problem is to cut rectangular holes into the side base rib plates and extend the width of the casting so that it bridges across the cylinder opening but is supported by the side rib plates (figure 15).

In this configuration, leg cylinder loading is transferred directly to the side rib plates of the base structure entirely through base metal contact, and is not dependent on the weldments to achieve this load transfer.

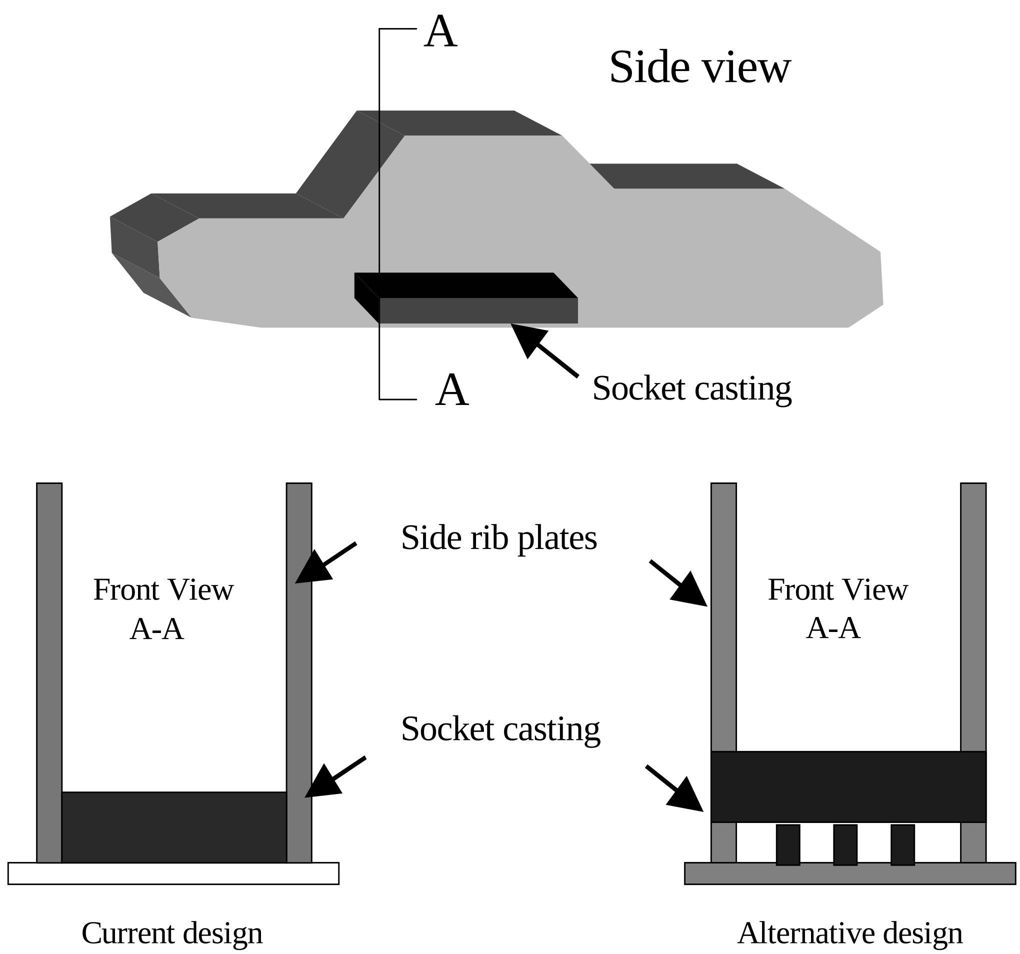

Figure 15 Conventional and alternative leg cylinder casting design

Corrosion Control - Some steps can be taken to circumvent the problems caused by corrosion. The most convenient approach is to try to protect the shield from the environment. For shield supports, this mostly applies to painting with an industrial paint that is resistant to the wet mine environment. However, for some components such as the pins and clevises where there is considerable wear due to the kinematics of the shield during load application, painting or even plating with more resistant material is not an option. Impregnated pins with zinc phosphate through sheridizing has proven beneficial, but the effectiveness is limited due to the wear in the joint.

Tests have shown that compressive stresses on the surface of materials that are exposed to the environment will not necessarily minimize corrosion-fatigue crack initiation, but they can reduce the possibility of crack growth and thereby prevent failure from occurring. This could be done by induction hardening the joint pins. The concern with this approach would be that the induction hardening might make the pins more brittle.

Material Toughness - The strength of materials approach essentially ignores the toughness of the material, which as described is the most significant material property for fracture control. There is a tradeoff in the use of high strength steels if they provide superior strength but reduced toughness with greater chance for failure. Since the author is not familiar with the German and British steels used in the shield construction, no specific recommendations are made, but the issue should be investigated with the shield manufacturer when new shields are purchased.

NEW DESIGN FEATURES AND GOALS FOR THE NEXT GENERATION OF SUPPORTS

1. **100,000 Cycle Life Expectancy –** The increases in life expectancy realized during the past 10-20 years should continue in the near future. It is not inconceivable to have a shield survive 100,000 loading cycles. In order to reach this goal, some improvements in design may be necessary or at least closer attention will need to be paid to fundamental design practices. In particular, components will need to be sized such that stress levels are kept at moderate levels with respect to the yield strength of the steel. Stress concentrations due to sharp changes in geometry must be avoided and weldments must be of high quality. More corrosion resistant materials may be used in certain areas to reduce stress corrosion. Make sure that the link bores have sufficient bearing areas to avoid high levels of stress and allow for the additional stresses caused by corrosion in the design of the link bores.

2. **Hydraulic Diagnostic Capability –** All shields will experience leakage in the leg cylinders or other hydraulic components that degrade the support capability. An algorithm should be specifically written into the control computer that monitors leg pressure histories that will provide the longwall coordinator with a record of bad leg cylinders that need to be repaired. Another option is to have the computer reset leg cylinders that are leaking below a designated setting pressure. While this capability exists on some modern faces, it should become a standard part of the operating system, and a report should be written to notify the operator when these events are occurring.

Observations of the relative positions of the cylinder staging can be used to identify cylinder problems and the cause of hydraulic leakages. One 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. Full extension of the bottom stage can be determined by analysis of the leg pressure data following the setting operation. When the bottom stage is fully extended, there will be a period of nearly zero increase in leg pressure until the top stage is sufficiently pressurized to offset the stress developed in the cylinder casing by the setting pressure in the bottom stage (figure 16) (AISC, 1980).

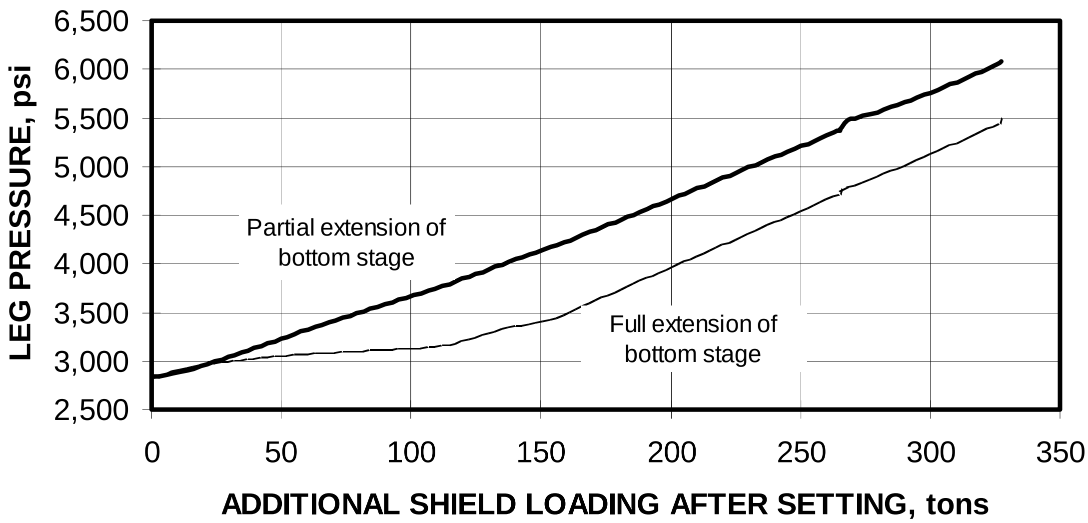

Figure 16. Difference in hydraulic pressure measurements when bottom is fully or partially extended

This information can also be used to track the percentage of time that the shield is set with reduced setting pressure due to full extension of the bottom stage. When this occurs, load development following the setting load should be monitored and analyzed to see if the reduced setting load results in higher levels of loading following the setting action.

Relative changes in staging position can also be used to detect leakages. Some possibilities are shown in table 1. The capability to track leg staging does not exist on current shield designs, but it is something that could improve the hydraulic diagnostic capability.

Component Failure	Bottom Stage Movement
Staging check valve	Up
First stage seals	Down
Second stage seals	Up
Pilot operated check valve ..	Down
Yield Valve	Down

Table 1. Stage movements associated with internal component failures

3. **Smart Load Control –** There is evidence to suggest that shield life can be improved by minimizing the load development on the shield, particularly since the design stress levels provide only a small margin of safety relative to fatigue effects and long term life expectancy.

   The benefits of derating a shield by installation yield valves which operate at lower pressures to reduce the total loading on the shield were discussed earlier in the paper. Another option would be to have programmable valves that the user can set without the need to physically change them out. This would allow the user to have some control over the rated capacity of the support, and to derate it if the full capacity is not needed.

   A better approach would be to optimize the use of the capacity that is available. With 1,200 tons of support capacity available in modern shields, it is doubtful that all this capacity is needed all the time. If the capacity could be used only when it is needed, then adequate ground control could be achieved and optimum utilization of the shield would be realized while minimizing the duty cycle of the support. To a large extent the shield loading is dictated by the setting pressures, which typically represent about 70 pct of the available shield capacity. A challenge for future shield designs would be for the control computer to optimize the set pressure by monitoring the load development history, and adjusting the set pressure to minimize total shield loading once a ground reaction curve for the longwall face is established. The idea of the ground reaction curve is to measure the ground response in terms of the support load density. Essentially, the goal is to not over support the ground, which may in fact cause more harm that good. The ground behavior can be measured in terms of convergence, which will manifest itself in shield loading. Generally speaking, the setting pressure is beneficial only if it controls the subsequent ground behavior or face convergence. Hence, there is probably some nominal setting pressure that is required, as well as some upper limit in which there is no benefit to further increases in setting pressure, and a region in between these two extremes where the benefit is measured in terms of the amount of convergence that is occurring. Hence, by monitoring the load development history of the support for a few cycles, and then lowering the set pressure until subsequent loading increases beyond the baseline, an optimum set pressure could be derived. By incorporating an algorithm into the control module, the set pressure could be adjusted as the conditions change to continually optimize the support capacity utilization.

   Another possibility is to have reduced setting pressures on sets of shields. For example, every other shield could be set at a reduced setting pressure. The concern here would be if that causes increased loading on the neighboring shields, then this practice would not that helpful since it would be a tradeoff of reducing the loading in some shields at the expense of others. However, this information could be obtained if the loading histories were monitored.

4. **Lubricated Link Joints –** Pin joints are necessary to accommodate the kinematics of a shield, but these joints are by far the leading cause of structural rebuild. Design recommendations have previously been made regarding improving the structural margin of safety by adding more contact area to offset the problems associated with distortion of the clevis due to wear, eccentric loading of the joints due to lateral canopy movements, and corrosion effects which reduce the

effective contact area and cause stress concentrations. Efforts should continue to enhance the use of wear resistant materials such as impregnating the pins with zinc phosphate, but consideration should also be given in future shield designs to a lubricated joint to reduce the wear and damage that occurs in these critical areas of the shield structure.

5. **Composite Material Design –** Even with the use of high strength steels, modern shields weigh as much as 30 tons. Weight is a major barrier in increasing the shield widths beyond 2.0 meters with the current steel constructions. Composite materials of equivalent strength weigh only 1/4 that of steel fabrications. While there are several engineering and economic issues that need to be explored before the feasibility of using high technology composite materials for shield construction can be determined, this could lead to a new generation of shield supports in the future. Axially loaded components such as lemniscate links might be one to examine first, and perhaps only sections of the other components could be fabricated from composites, but it definitely an area worth investigating.

6. **Forecasting Periodic Weighting and Heavy Roof Loading–** Most modern shield systems are capable of capturing shield loading histories to the point where we are overloaded with data. This data, if properly managed can be useful in evaluating leg cylinder leakage and optimizing setting pressures as suggested in above. Another area is of value is the prediction of periodic weighting intervals. There has been some research in this area already. For example, NSA Engineering Inc developed a shield monitoring program that couples with their GeoGuard™ software [Sanford et al. 1999]. The system was recently tested in an Australian mine where severe face weighting was observed resulting in hazardous face conditions and weeks of lost production.

7. **Advanced Component Load Measurement** – Currently, only the leg cylinder pressure is monitored. No loading information is obtained on any other components. It would not be difficult in the design process to include strain gages on selected components which could be monitored by the computerized data acquisition system. This need not be done on every production shield, in fact 2 or 3 shields could serve as instrumented shields and provide valuable information on the actual load conditions observed underground. This information could then be used to refine performance testing as well as help to identify load conditions that actually contribute or cause structural failures. Even measurement of the link loading alone would provide valuable information that is currently not available.

8. **Constant Set Leg Cylinder Design –** Current U.S. shields employ a two-stage cylinder design where the first stage extends and retracts first. This operation typically causes the first stage to be near full extension most of the time. In addition, seal leakage which occurs on almost all aging shields causes the bottom stage to extend outward and further promotes full extension of the bottom stage. Since the setting force and the subsequent capacity of the shield to resist roof loading is reduced in proportion to the area differential between the top and bottom stage when the bottom stage is fully extended, this is not a good design to ensure that the full capacity of the shield is utilized. In other words, why buy a 1,000 ton shield when its performance is degraded to a 500 ton shield a significant portion of the time. There are alternative designs available, most

notably the concept employed by Fazos Inc., which do not use the conventional two-stage design utilized in most modern shields. The Fazos design utilizes a central core to eliminate the use of independently acting stages (figure 17). While this design works, it has not be adopted by the major shield manufacturers for whatever reason. An alternative approach would be to configure the standard two-stage design with a system that would cause the top stage to extend first. This could be done by using a nominal hydraulic pressure in the retract annulus of the bottom stage during the extend operation (figure 18). For current shields, a mechanical device (strap or chain holster) could be built that would attach to cylinder casing and the base that would prevent the bottom stage from extending. This is not something that would be used on every mining cycle, but would be done periodically as part of a preventive maintenance program to restore full setting capability to the leg cylinders which are routinely at full bottom stage extension.

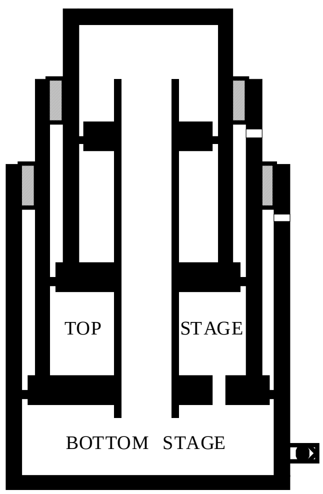

Figure 17 Constant set leg cylinder design developed by Fazos, Inc.

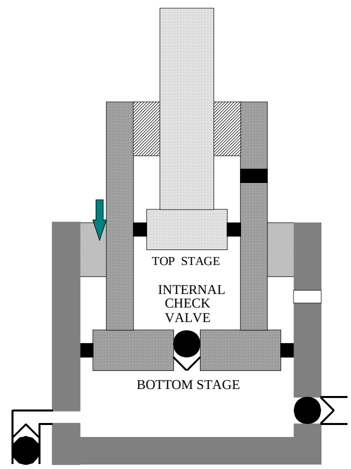

Fig. 18 Maintaining nominal pressure on bottom stage to force top stage out first

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