Performance and Safety Considerations of Hydraulic Support Systems

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ABSTRACT

Hydraulic cylinders are used in several roof support systems, such as longwall shields and mobile roof supports, to provide critical ground control. Many state-of-the-art hydraulic support systems operate at pressures as high as 7,000 psi to provide the necessary support capacities. Pressure in the upper stages of multi-stage cylinders can be intensified by a factor of 2 or 3 providing pressures of 20,000 psi or greater. A proper understanding of the operation of these high pressure systems is necessary to safely maintain and repair these support systems. Likewise, the performance characteristics need to be fully understood to evaluate the impact of design parameters on the capability of the support to maintain effective ground control. This paper examines the basic operating principles of state-of-the-art hydraulic cylinders and discusses relative issues pertaining to: (1) setting loads, (2) support stiffness, (3) yielding behavior, (4) errors in assessing support loading, and (5) hydraulic failure mechanisms and how to detect them.

INTRODUCTION

Hydraulic support systems are used frequently in underground mining to provide critical ground control. Some examples of their applications include: (1) shields which provide ground support along the working face in longwall mining, (2) mobile roof supports which protect miners from caving strata during retreat mining pillar extraction operations, and (3) temporary support systems such as those used on bolting machines which are used to support the mine roof while more permanent support can be installed.

Hydraulic roof support systems have two major advantages over other types of supports. First, they have the flexibility to extend and retract, thereby allowing the same support to be installed in a wide-range of mining heights. Second, hydraulic supports can be pressurized to provide active roof support. By actively setting the support against the mine roof and floor, hydraulic support systems close any gaps within the immediate roof structure, creating a laminated roof beam that is much stronger and more stable. In contrast, passive roof supports such as wood cribs and timber posts, develop load carrying capacity only through the convergence of the mine roof and floor. The downward movement of the roof weakens and eventually causes failure of the roof beam. In addition, an active hydraulic support creates a stress concentration at the support that acts to break off a roof fall, whereas there is a much greater probability of a roof fall riding past the support into the working area with a passive support system.

On the surface, it appears that the performance of hydraulic supports is straight forward, and that little consideration needs to be given to the design, selection, and operation of hydraulic roof support systems. Upon closer examination, it can be seen that the performance of hydraulic support systems is dependent upon several factors that can influence ground control capabilities and safe operation of these popular support systems. The purpose of this paper is to examine the characteristics of hydraulic roof support systems that impact ground control and operator safety.

HYDRAULIC CYLINDER DESIGN AND BASIC OPERATING PRINCIPLES

The support capacity of all hydraulic roof supports is provided by one or more hydraulic cylinders. The remaining structure in these supports is simply to transfer load to the hydraulic cylinders to provide the necessary work to support the weight of the mine roof and control the movement of the mine roof and floor.

The basic operation of a hydraulic support can be described as follows (see figure 1). A hydraulic power supply pumps fluid into a cylinder(s) on the roof support structure. The fluid acts against a piston, causing the piston and attached steel rod to displace outward. This displacement will continue with very little hydraulic pressure until the support is set against the mine roof and floor. The hydraulic pressure will then increase rapidly until the full pump pressure is reached. After the pump supply is

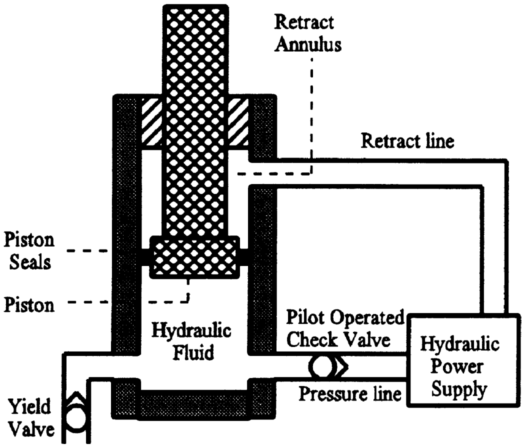

Figure 1.-Basic components of a hydraulic roof support.

turned off or isolated from the support, this pressurized hydraulic fluid is trapped inside the cylinder by a pilot-operated check valve. The pressure of the hydraulic fluid inside the cylinder is then intensified in proportion to any increase in roof loading. A yield valve limits the maximum pressure inside the cylinder to prevent excessive loading that would damage the cylinder. Most state-of-the-art hydraulic cylinders used in modern mine roof support structures are double acting cylinders, meaning that they are hydraulically powered to both extend and retract (see figure 1). This requirement stems primarily from longwall shield supports, where powered lowering of the shields is required to minimize the advance cycle time. Powered lowering of the support is achieved by pumping fluid inside the retract annulus (see figure 1), while at the same time applying pilot pressure to open the check valve to allow fluid from inside the main cylinder cavity that supports the weight of the mine roof to escape back to the hydraulic power supply tank.

The previous example described the basic operation of a single-stage cylinder, where extension and retraction is provided by one stage. Many supports, including longwall shields and mobile roof supports, utilize multi-stage hydraulic cylinders. Figure 2 depicts a two-stage hydraulic cylinder used on a state-of-the-art longwall shield, and figure 3 depicts a three-stage hydraulic cylinder utilized on a state-of-the-art mobile roof support. For discussion, the stages are referenced starting with the largest diameter as stage 1, and each successively smaller diameter as stage 2, stage 3, etc., or in reference to their location with designations of bottom (stage 1), middle when applicable, and top stage. Incorporating more stages into a leg cylinder design generally allows for a lower collapsed height, combined with an equal or greater maximum working height to provide operation in a wider range of mining heights than fewer stages would permit.

The basic operating principles of these multi-stage designs are the same as the single stage hydraulic cylinder previously described, but there are some noteworthy differences relative to how the individual stages perform.

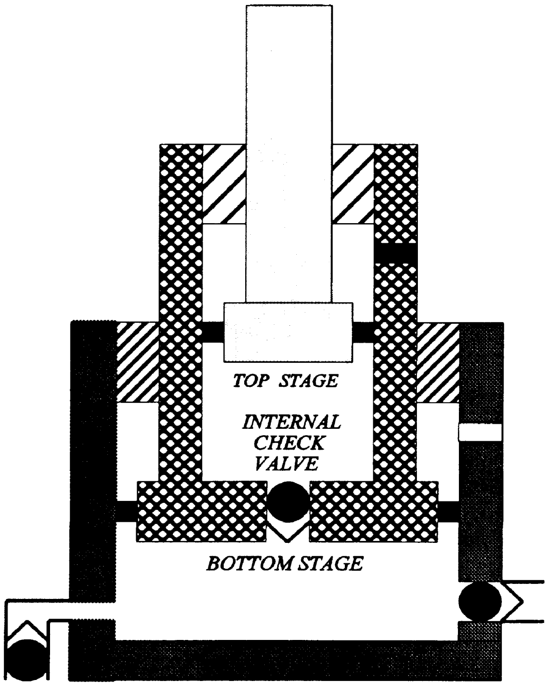

Figure 2.-Two-stage hydraulic cylinder.

1. In multi-stage cylinders used on most mining support systems, the largest (diameter) stage extends and retracts first, followed in succession by the stage with next smallest diameter. For example, in a three-stage leg cylinder, the bottom stage would extend first, followed by the middle stage, and then the top stage. Each stage will extend until it is fully stroked before the next stage will begin to extend.
2. A check valve is incorporated into the piston(s) of all but the top stage. For example, in a two-stage leg cylinder, a check valve would be installed in the bottom stage piston. This check valve functions to allow hydraulic fluid to flow from the bottom stage to the top stage to cause the top stage to extend during the setting operation whenever the bottom stage is fully extended. It also isolates the bottom stage from the top stage to allow the hydraulic fluid to be intensified in the top stage once the support is actively set against the mine roof and floor. This is necessary to allow the top stage to carry the same load as the bottom stage. A three-stage leg cylinder would incorporate check valves in both the bottom stage and middle stage pistons as illustrated in figure 3.

How the staging functions to provide the necessary support capacity is essential to understanding the operation of multi-stage leg cylinders. For proper operation of the support cylinder to occur, force equilibrium must be satisfied for each stage, meaning each stage must carry the same load. This requires different hydraulic pressures in each stage, since the area of each stage is different. Mathematically, this requirement is expressed by equation 1.

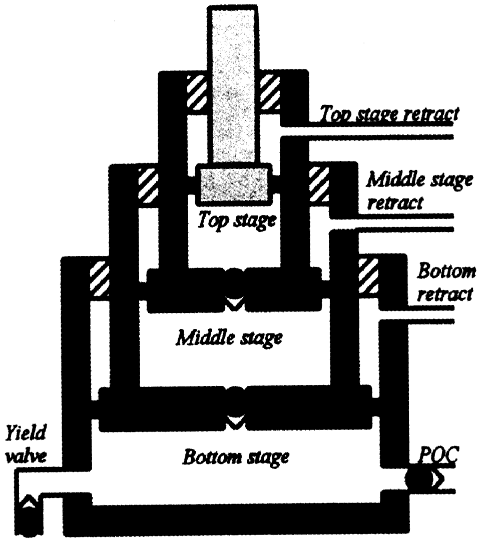

Figure 3.-Three-stage hydraulic cylinder.

$$A_1 * P_1 = A_2 * P_2 = A_n * P_n \quad (1)$$

where A_1 = area of bottom stage, sq. in;
P_1 = pressure in bottom stage, psi;
A_2 = area of second stage, sq. in;
P_2 = pressure in second stage, psi;
A_n = area of n^{th} stage, sq. in;
P_n = pressure in n^{th} stage, psi.

Using a two-stage cylinder as an example, if the top stage area (A_2) is one half (50 pct) that of the bottom stage area (A_1), the pressure in the top stage (P_2) will be twice that of the hydraulic fluid in the bottom stage (P_1).

$$P_2 = \frac{A_1}{A_2} * P_1 \quad (2)$$

For a three-stage leg cylinder,

$$P_2 = \frac{A_1}{A_2} * P_1 \quad (3)$$

$$P_3 = \frac{A_2}{A_3} * P_2 \quad (4)$$

where P_1 = pressure in bottom stage, psi;
P_2 = pressure in middle stage, psi;
P_3 = pressure in top stage, psi;
A_1 = area of bottom stage, sq. in;
A_2 = area of middle stage, sq. in;
A_3 = area of top stage, sq. in.

The extension of specific stages on a hydraulic support system, such as a longwall shield or mobile roof support, at a particular point in time (cycles of operation) depends on the history of the operating heights of the support. When the support is initially raised from a fully collapsed position, the bottom stage will extend first. If the mining height is greater than the stroke of the bottom stage, the second stage will extend until roof contact is made, or in the case of a three-stage cylinder, the third stage will extend after the second stage is fully stroked to achieve the roof contact. On subsequent cycles, the upper stage(s) will remain at the initial extension(s) until: (a) the mining height is increased beyond that of the initial cycle, or (b) the support is sufficiently lowered such that the bottom stage is fully collapsed. Assuming the support is not lowered to the point where the bottom stage is fully collapsed, the upper stage will extend beyond the initial extension only when the mining height is increased. In essence, the bottom stage will be fully stroked when: (a) the support is initially raised from a collapsed position, and (b) on the mining cycle that establishes a **new maximum operating height**, whenever the support height is higher than it has been on all previous mining cycles. On all other cycles, the bottom stage extension will reflect changes in mining height relative to the initial mining height and the maximum operating height at which the support was utilized.

A two-stage hydraulic cylinder, as shown in figure 2, is used as an example to illustrate these concepts. As shown in figure 4, the initial setting of the support causes the bottom stage to be fully extended (24-in stroke) and a 12-in (partial) extension of the top stage. If the roof-to-floor mining height is reduced on second operating cycle by 3 in, the bottom stage extension now will be 21 in while the top stage extension will remain at 12 in. Now if the mining height is increased by 6 in from that of the second cycle, the bottom stage will again be fully extended (24-in stroke) and the second stage extension will increase to 15 in on the third cycle. This exercise can continue as shown in figure 4. As shown in this exercise, the top stage extension on any cycle will equal the initial extension plus the incremental increase in mining

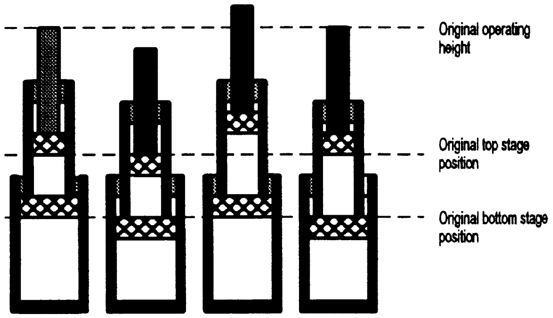

Figure 4.-Stage extensions produced by changes in operating height.

height beyond the initial mining height. The top stage extension will never be less than the initial extension unless the support is lowered to the point where the bottom stage is fully retracted. The bottom stage extension will fluctuate with changes in mining height on each cycle, and will be fully stroked whenever a new maximum operating height is attained.

ACTIVE (SETTING) LOADS

Hydraulic support systems can be actively set against the mine roof and floor by pressurizing the hydraulic cylinders. The force that is exerted against the mine roof and floor is dependent upon the size of the cylinder and the hydraulic (pump) pressure. In multi-stage cylinders, the setting force can be determined by measuring the pressure in any stage and multiplying that pressure by the (piston) area of that stage. It is important to remember that the pressure in all but the bottom stage is intensified during the setting operation, and only the bottom stage will be at pump pressure once the support is set (assuming none of the stages are at fully stroked). In most multi-stage hydraulic cylinders, such as those used on longwall shields and mobile roof supports, the hydraulic pressure is measured only in the bottom stage, hence the pump pressure times the bottom stage area should be used to calculate the setting force. The total setting force for the support is simply the sum of each individual hydraulic cylinder forces.

If one or more stages is fully stroked, the setting force will be diminished. The stage that is fully extended no longer transfers all of its force to the mine roof and floor, instead part of it is consumed by tensioning the cylinder casing as the piston is forced against the mechanical stops that limit its travel. And, the pressure in the stage above the fully extended stage will not be intensified, but instead will be at pump pressure. The setting force will always equal the pump pressure times the area of the largest diameter stage which is not fully extended. Hence, in a two-stage cylinder, the setting force will equal the pump pressure times the second stage area whenever the bottom stage is fully extended. In a three-stage cylinder, the setting force will equal the pump pressure times the second stage area whenever the bottom stage is fully extended, and the setting force will equal the pump pressure times the third stage area whenever both the bottom and middle stages are both fully extended.

The reductions in setting force due to full extension of stages can be very large. Table 1 below documents the actual reductions in setting force for a state-of-the-art, 700-ton, two-stage, longwall shield and a 600-ton, three-stage, mobile roof support.

Table 1. Reduction in setting force due to stage extensions.

	ACHIEVED SETTING FORCE, PCT OF FULL SETTING FORCE	
STAGE CONDITION	**700-ton Longwall Shield**	**600-ton Mobile Roof Support**
No stage fully extended	100	100
Bottom stage fully extended	54	55
Bottom and middle stage fully extended	N/A	30

Recalling the operation of the hydraulic cylinder previously described, the setting force will be diminished whenever the bottom stage is fully extended, which occurs on the operational cycle where a new maximum operating height is attained. The setting force will be restored to its full capability whenever the support is operated at a height less than the highest operating height on any previous operating cycle.

SUPPORT STIFFNESS

Stiffness is a measure of how quickly the support develops its load carrying capacity in response to roof-to-floor convergence. The stiffness of hydraulic support systems is examined in terms of the parameters that affect the support stiffness and the impact of support stiffness on ground control.

Discussion of General Stiffness Principles

The stiffness of a hydraulic cylinder can be determined theoretically using the following principles. Full-scale testing of longwall shields and mobile roof supports in NIOSH's Mine Roof Simulator load frame verify that these principles are valid.

The various stages of a multiple stage leg cylinder act in series to provide an equivalent stiffness as described by equation 5.

$$\frac{1}{K_{eq}} = \frac{1}{K_1} + \frac{1}{K_2} + \ldots\ldots + \frac{1}{K_n} \qquad (5)$$

where K_{eq} = equivalent stiffness of the leg cylinder
K_1 = stiffness of stage 1
K_2 = stiffness of stage 2
K_n = stiffness of stage n

For a two-stage and three-stage leg cylinder this equation can be transformed as follows:

$$K_{\text{Two stage}} = \frac{K_1 * K_2}{K_1 + K_2} \qquad (6)$$

$$K_{\text{Three stage}} = \frac{K_1 * K_2 * K_3}{K_1 * K_2 + K_1 * K_3 + K_2 * K_3} \qquad (7)$$

The stiffness of the individual stages can be determined using the bulk modulus of the oil as shown in equation 8. The manufacturer of the oil can provide accurate data on the bulk modulus. A value of 320,000 psi is recommended in the absence of manufacturer data. This value can also be used for water-oil emulsions such as those used in longwall shields.

$$K_n = \frac{A * \beta}{L} \qquad (8)$$

where K_n = stiffness of stage n, lbs/in
A = area of stage n, in^2
β = bulk modulus of the oil, psi
L = stage extension, in

Since the cylinder structure (i.e., casing) is not perfectly rigid, the stiffness of the cylinder structure should also be considered in the calculation of the overall leg cylinder stiffness. The cylinder casing can also be considered to act in series with the hydraulic stiffness to provide a total stiffness as shown in equation 9. The stiffness of the cylinder casing will vary depending on the design of this steel structure. A study of mobile roof support hydraulic cylinders revealed cylinder structural stiffness of 2,300 kips/in for a two-stage cylinder and 3,200 kips/in for a three-stage cylinder (kip = 1,000 lbs).

$$K_{\text{System}} = \frac{K_{\text{Hydraulic}} * K_{\text{Cylinder}}}{K_{\text{Hydraulic}} + K_{\text{Cylinder}}} \qquad (9)$$

where K_{system} = Overall leg cylinder stiffness, lbs/in
$K_{\text{hydraulic}}$ = Hydraulic (oil component) stiffness, lbs/in
K_{cylinder} = Cylinder structural stiffness, lbs/in

Key Points in Determining Support Stiffness

A close examination of these stiffness principles reveals several key points regarding the determination of the stiffness of hydraulic support systems.

1. The stiffness of a hydraulic roof support is not significantly affected by the setting pressure.
2. The stiffness of a hydraulic roof support is a nonlinear function of operating height, decreasing exponentially as the height increases.
3. The diameter of the hydraulic cylinder primarily controls the stiffness of the hydraulic support with increased stiffness as the diameter of the cylinder increases. However, an important point to remember in multi-stage cylinders is that the smallest (diameter) stage will have the least stiffness and therefore largely control the overall stiffness of the support. This is why a three-stage hydraulic cylinder will always be less stiff than a two-stage hydraulic cylinder with the same size (diameter) bottom stage.
4. The stiffness of a multi-stage hydraulic cylinder is also dependent on the extension of the respective stages. The stiffness of each stage decreases exponentially as the stage extension increases. The top stage will produce the most influence on the support stiffness. The stiffness of the support increases dramatically when the top stage is not extended at all or only very slightly extended. In this condition, the support can be as much as 10 times stiffer than when the all stages are extended greater than 75 pct of their stroke. A minimal extension on the top stage of 3 in reduced the stiffness of a mobile roof support two-stage leg cylinder by 45 pct compared to no extension of the top stage.
5. In supports using multi-stage hydraulic cylinders, the same overall support stiffness can occur at two different operating heights, depending on the combination of stage extensions. In other words, 5 in of bottom stage extension and 15 in of top stage extension will not produce the same stiffness as 15 in of bottom stage extension and 5 in of top stage extension. Figure 5 depicts a stiffness envelope for a 150-ton two-stage hydraulic cylinder used on a 600-ton mobile roof support. For this particular cylinder, a stiffness of 400 kips/in occurs at operating heights of 64 and 75 in. Likewise, at a 64 in operating height, the stiffness can vary from 400 to 620 kips. A theoretical stiffness envelope can be determined by calculating the individual stage stiffness (eq. 8) and the system stiffness (eq. 9) at different stage extensions.

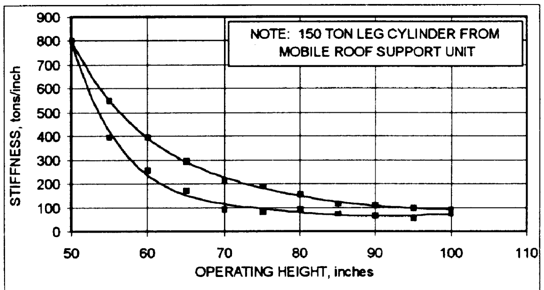

Figure 5.-Stiffness envelope for a two-state 150-ton hydraulic mobile roof support cylinder.

6. The total displacement in a hydraulic cylinder will equal that of the roof-to-floor convergence, but this displacement will be distributed differently among the stages in proportion to the stiffness of the individual stage. The stiffest stage will move (displace) less than the softest stage. This means that most of the convergence will occur in the top stage of multi-stage hydraulic cylinders.

Impact of Stiffness Issues on Ground Control

A stiffer support will develop more load carrying capacity for the same roof-to-floor convergence than will a softer support (fig. 6a). Conversely, a softer support will allow greater roof movement to occur, assuming that the supporting force is controlling the roof movement (fig. 6b).

The following recommendations are made regarding design considerations for hydraulic roof support systems in regards to the stiffness of the support.

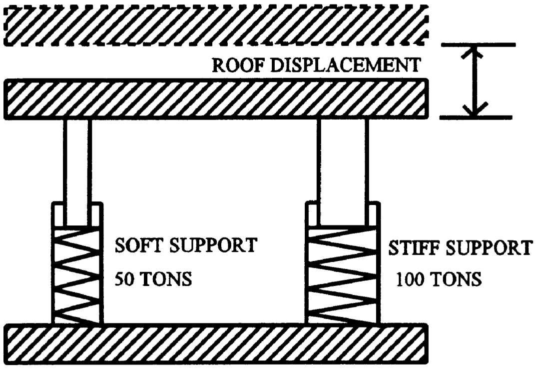

Figure 6a.-Stiffer support develops more loading due to roof and floor movement.

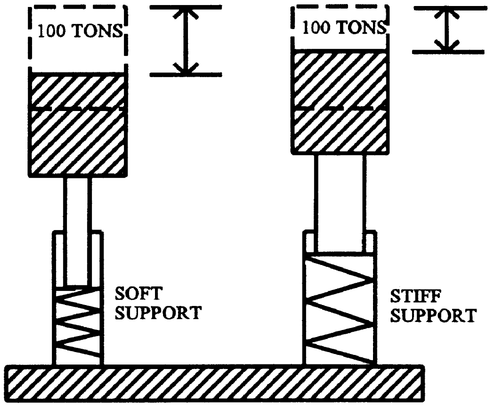

Figure 6b.-Softer support will allow more roof movement to occur.

1. Two-stage systems should be used whenever possible, since two-stage systems are stiffer than three-stage systems for the same (bottom stage) cylinder size and yield pressures. If three-stage cylinders are required to obtain the desired operating range, consideration should be given to making the top stage diameter sufficiently large to provide the required stiffness, even if this requires a larger diameter bottom stage.
2. Since hydraulic support systems are considerably less stiff at high operating heights, they are less efficient at controlling roof movement when used at high operating heights. Therefore, when designing a support, the collapsed height should be no lower than is necessary. This practice will minimize the operating range and provide the least reductions in support stiffness as the operating height increases.

Since the stiffness of the support changes as function of the leg staging, the interpretation of loading on hydraulic support systems may require knowledge of the leg staging, particularly if the support forces are not controlling the main roof movements which is generally the case in longwall mining. In essence, the developed support loading due to roof/floor movement will be greater when the support stiffness is greater. This issue also complicates the utilization of load rate monitoring devices, such as those being developed for mobile roof supports to be used to assess impending strata caving. The rate of loading is likely to be dependent on the stiffness of the support, hence changes in the support configuration due to leg staging and operating heights will cause the loading rates to change for the same roof behavior (movement).

YIELDING BEHAVIOR

Yield valves are normally connected to the bottom stage of multi-stage hydraulic cylinders to provide overload protection. These valves open whenever the pressure exceeds the design threshold and allows the pressurized fluid to escape from the bottom stage of the cylinder. This loss of fluid causes the pressure to drop in the bottom stage until the valve reseats. The reseating pressure is typically about 90 pct of the yield pressure, hence the support capacity will drop by approximately 10 pct when the yield valve opens. As the pressure drops in the bottom stage, a force imbalance occurs between the top and bottom stage (in a two-stage hydraulic cylinder), which causes the bottom stage to lower until force equilibrium between the two stages is attained. The lowering of the bottom stage is associated with lowering of the mine roof, hence excessive yielding is not desirable from a ground control perspective. Successive yielding events will eventually cause the bottom stage to be fully collapsed, at which time the top stage will begin to collapse. Additional yielding can continue until the top stage is fully collapsed, at which time the support is considered to be iron-bound.

How much the bottom stage lowers due to yielding depends on three factors: (1) the area of the bottom stage, (2) the extension of the bottom stage, and (3) the yield pressure and reseating pressure of the yield valve. The reduction in support height due to yielding which equates to roof lowering will be more for large extensions of the bottom stage than for small extensions of the bottom stage. The magnitude of bottom stage lowering due to yielding can be calculated using equations 10 and 11. Using a 700-ton longwall shield with a bottom stage diameter of 300 mm and a yield pressure of 6,389 psi as an example, the bottom stage of each hydraulic cylinder will drop approximately 0.028 in during yielding if the bottom stage was extended 14 in when yielding began. A reduction in support loading of 70 tons would be caused by the yielding. As the support yields, it also becomes stiffer due to the reduction in operating height (stage extension). Hence, less roof movement will be required to produce additional yielding.

$$\Delta V = \frac{\Delta P * V}{\beta} \tag{10}$$

where Δ V = change in volume of fluid in bottom stage of cylinder, in^3

Δ P = change in hydraulic pressure in bottom stage of cylinder, psi

ΔP = Yield pressure - reseating pressure, psi
V = Volume of fluid in bottom stage when yielding, in^3
V = Area of bottom stage times extension of bottom stage, in^3
β = bulk modulus of oil, psi (i.e., 320,000 psi)

$$\Delta L = \frac{\Delta V}{A} \qquad \textbf{(11)}$$

where ΔL = reduction in bottom stage extension due to yielding, in
ΔV = reduction in volume of fluid in bottom stage due to yielding, in^3
A = Area of bottom stage, in^2

ERRORS IN ASSESSING SUPPORT LOADING

Support loading is determined from measurement of the pressure in the bottom stage of the hydraulic cylinder. Since the pressure increases in direct proportion to the increase in support loading, this provides an accurate assessment of the roof loading through the full loading cycle.

However, when the bottom stage is completely extended to its full stroke, a portion of the increase in roof loading after the support is set against the mine roof and floor will not be detected by changes in hydraulic pressure in the bottom stage (see figure 7). The reason for this period of undetected roof loading is that when the bottom stage is fully extended, the bottom stage piston is being held against the mechanical stops with a force exerted by the pump pressure at the time the support was set. The pressure in the bottom stage will only increase when this piston is moved off the stops and begins to compress the hydraulic fluid in the bottom stage. In order for this to happen, the pressure in the upper stage, which is at pump pressure when the support is set, must increase to cause a force in the upper stage that exceeds the setting force in the bottom stage. The additional roof loading that is required to produce this additional pressure in the upper stage is the roof loading that is undetected by the gages measuring hydraulic pressure in the bottom stage.

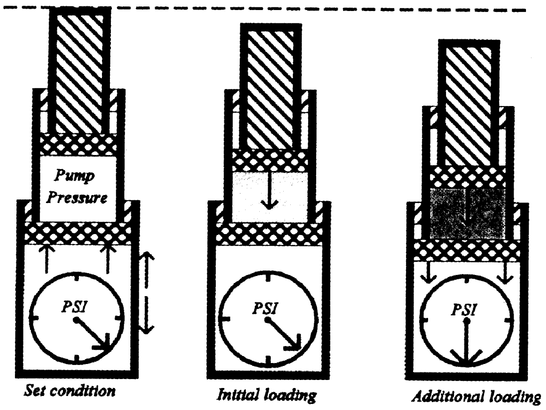

Figure 7.- Initial roof loading after the support is set will be undetected by changes in bottom stage pressure whenever the bottom stage is fully extended.

The mechanics of the pressure development in the various support stages can be described by examination of equilibrium requirements for each individual stage, realizing that each stage must carry the same load (1). The undetected roof loading for a two- and three-stage hydraulic cylinder with the bottom stage fully extended can be calculated using equation 12. Equation 13 must be used for a three-stage cylinder where both the bottom and middle stages are fully extended. An examination of these principles indicates that the period and magnitude of undetected roof loading will increase as the setting pressure increases. The undetected roof loading occurs immediately after the support is set. The remaining shield capacity (rated capacity minus setting load and undetected load) will be measured by the pressure gages.

$$URL_{Two\text{-}stage\ /\ Three\ stage} = \frac{A_2 * P_2 - A_1 * P_1}{2000} \qquad (12)$$

$$URL_{Three\text{-}stage} = \frac{A_3 * P_3 - A_1 * P_1}{2000} \qquad (13)$$

where URL = undetected roof load, tons
A_1 = area of first (bottom) stage, in^2
A_2 = area of second stage, in^2
A_3 = area of third stage, in^2
$P_1 = P_2 = P_3$ = setting (pump) pressure, psi

Figure 8 depicts undetected roof loading for the following state-of-the-art hydraulic support systems: (a) 700-ton (two-stage) longwall shield, (b) 600-ton (two-stage) mobile roof support, and (c) 600-ton (three-stage) mobile roof support set at full pump pressure. It is seen from this figure that the unrecorded

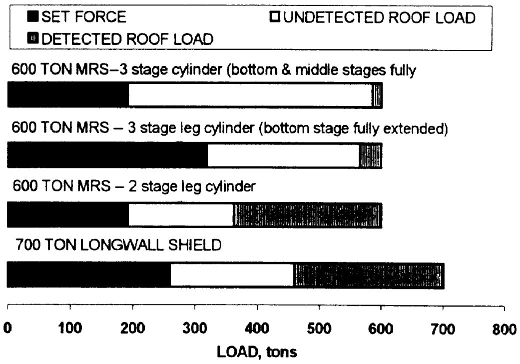

Figure 8.-Magnitude of undetected roof loading for various support systems.

roof loading is quite large. For example, approximately 200 tons of undetected roof loading, which represents 46 pct of the remaining shield capacity, will occur on the 700-ton longwall after it set against the mine roof and floor. The undetected roof loading for mobile roof support using three-stage hydraulic cylinders can consume nearly the entire loading cycle (see figure 8).

HYDRAULIC FAILURE MECHANISMS AND HOW TO DETECT THEM

Hydraulic roof support systems depend on hydraulic fluid being maintained under pressure to provide the necessary supporting capability. Any condition that results in pressure loss reduces the capacity of these hydraulic roof supports. In many cases, the pressure loss will be internal such that the fluid loss is not noticeable. Sources of pressure loss and ways to detect them are described below.

SOURCES OF PRESSURE LOSS AND IMPACT ON SUPPORT CAPACITY

Pressure losses in hydraulic roof support systems are typically due to leakage of hydraulic fluid. The major components of a hydraulic support system were identified in figure 1 as follows: (1) bottom stage piston seals, (2) upper stage(s) piston seals, (3) pilot operated check valve, (4) yield valve, and (5) staging check valve(s). Each of these components must function properly to prevent leakage of hydraulic fluid that will result in pressure losses. Each of these component leaks 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 (assuming the leakage rates are greater than the pressure increases caused by any additional roof loading).

The change in volume required to produce pressure losses can be theoretically determined by equation 14. Assuming a drop of fluid measures 1/8 x 1/8 x 1/8 in and thereby consumes 0.002 in^3, table 2 shows the time in minutes necessary to produce pressure losses of 1,000, 2,000, 3,000, and 4,000 psi in the bottom stage of a longwall shield cylinder for a leakage rate of 10, 100, and 1,000 drops per minute assuming no additional roof movement or loading occurs. In a recent test of a longwall shield with a bad staging check valve and worn seals, 2,300 psi of setting pressure dropped to zero psi in approximately 4 minutes.

$$\Delta P = \frac{\beta * \Delta V}{V} \tag{14}$$

where Δ P = change in pressure, psi
β = bulk modulus of oil (i.e., 320,000), psi
Δ V = change in volume, in^3
V = original volume, in^3

Table 2. Time required to produce leg cylinder pressure losses.

Average Leakage Rate	Time in minutes required to produce designated pressure losses			
	-1,000 psi	-2,000 psi	-3,000 psi	-4,000 psi
10 drops/min	255.5	510.9	766.4	1021.9
100 drops/min	25.6	51.0	76.6	102.2
1,000 drops/min	2.6	5.1	7.6	10.2

1 drop = .002 in^3 = 1/8 x 1/8 x 1/8 in cube
10 drops = .02 in^3 ~ 1/4 x 1/4 x 1/4 in cube
100 drops = .2 in^3 ~ ½ x ½ x ½ in cube
1000 drops = 2 in^3 ~ 1-1/4 x 1-1/4 x 1-1/4 in cube
Note: Data in table 2 assumes a cylinder (bottom stage) area of 110 in^2 with a 15 in extension and an initial pressure of 4,000 psi.

Table 2 describes pressure losses relative to setting pressure of 4,000 psi in terms of *average* leakage rates. The leakage rate is governed by the pressure differential where the leak is occurring. Hence, the rate of leakage will decrease in time in an exponential fashion as the leakage causes a reduction in pressure differential.

The cooling of the hydraulic fluid can also be responsible for pressure losses in hydraulic support systems. This problem is much more prevalent on mobile roof supports than longwall shields, since each mobile roof support contains a hydraulic power supply, and the fluid which is heated by the pump is not cooled to ambient temperatures before it is pumped into the hydraulic cylinders. The steel in the cylinder then acts as a large heat sink to reduce the temperature of the fluid, which causes a reduction in volume and an associated pressure loss. The thermal expansion coefficient for commercial hydraulic oils ranges from 0.0003 to 0.0005 per degree F (2). Hence, a 10 degree change in temperature will change the volume of the fluid by 0.3 to 0.5 pct. On a mobile roof support with two-stage hydraulic cylinders, this would translate into a pressure loss of about 1,200 psi. Unlike the pressure losses caused by mechanical component leakages which result in no load carrying capacity, the temperature-induced pressure losses will decay to some non-zero value, meaning the support capacity will be diminished but significant capacity will remain.

Another source of pressure loss in hydraulic support systems is an extension of leg cylinders in the absence of additional roof/floor loading. This can be due to fracturing of immediate roof or floor strata or more likely the compaction of roof or floor debris (broken rock or loose coal). On two-leg longwall shields, the leg pressures can also be reduced if the canopy or base slides along the roof or floor due to the horizontal component of the leg forces. An analysis of the 700-ton longwall shield that has been used in previous examples, indicates that 0.11 in of extension of the operating height is sufficient to cause a 1,000 psi drop in leg cylinder (bottom stage) pressure. Like the temperature induced pressure losses, unintended extension of leg cylinders due to non rigid roof and floor boundaries tend to reduce the supporting force, but not completely eliminate it as is the case with the component leakages previously described.

DETECTION OF COMPONENT FAILURES

The first point to remember about hydraulic leaks is that in all cases there is a loss of pressure, and this pressure loss will continue until there is no pressure in the cylinder (assuming the leakage rates are greater than the pressure increases caused by any additional roof loading). A consistent decline in pressure on each operating cycle after the support is set against the mine roof and floor is an indication of a hydraulic leak. Significant pressure losses during idle shifts are also good indications of cylinder problems.

Observations of the relative positions of the cylinder staging can be used to identify cylinder problems and the cause of hydraulic leaks. As previously described, these leaks are often internal with no visible external fluid leakage. The first indication of internal leakages is when the bottom stage is consistently fully extended. Recalling the previous discussion on multi-stage cylinder operation, 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 stage extensions of leg cylinders on the same support. For example, on longwall shields the left and right leg should be at nearly the same extension. Some differences in extension may result from uneven roof heights across the width of the canopy, but these differences 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 9, is an indication of a hydraulic leak that can result in no support capacity. Table 3 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 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 extended less than the bottom stage on adjacent cylinders.

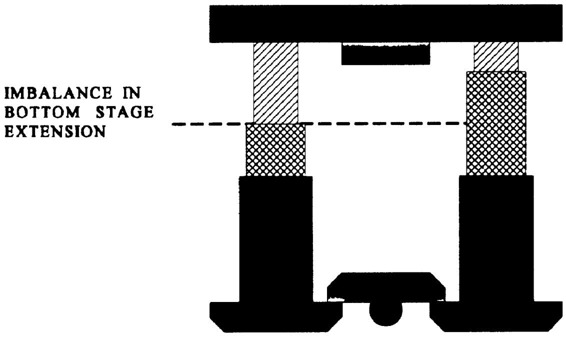

Figure 9.-Imbalance in stage extension is an indication of hydraulic leakages.

Table 3. 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.

COMPONENT FAILURE	Top Stage Movement	Bottom Stage Movement	Bottom Stage Pressure	Top Stage Pressure
Staging check valve	None	Up	0	0
First stage seals	None	Down	0	0
Second stage seals	None	Up	0	0
Pilot operated check valve	None	Down	0	0
Yield valve	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 10). 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.

REPAIR AND MAINTENANCE OF HYDRAULIC CYLINDERS

All hydraulic support systems will require repair and rebuild sometime during the life of the roof support system. Since these systems are operating at high pressures, safety should always be exercised when working with hydraulic cylinders. Only 300 psi of hydraulic pressure is required to produce a stream of hydraulic fluid that can puncture the skin and cause serious bodily harm. In addition, bacteria in hydraulic fluids can be toxic and cause serious infection and health problems if left untreated.

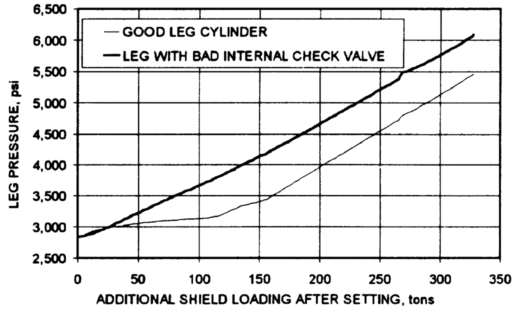

Figure 10.-Bottom stage pressure response with bad stage checking valve.

Safety should also be exercised when removing the hydraulic cylinders from the roof support. Both longwall shields and mobile roof supports will become unstable once the hydraulic cylinders are removed, and it is critical that the structure be properly supported when removing these supporting elements. Repairs should be made by a reputable shop with expertise in hydraulic systems. It is critical that the cylinders be load tested before and after the repair to make sure that all components are working properly. Rebuilding of a hydraulic cylinder will generally entail replacing all seals and check valves, machining and rechroming the cylinders bores and pistons to bring them back to design specifications.

When the cylinders are rebuilt, the ports are often plugged to keep the fluid in the cylinder. One common mistake that is made is not to remove the retract port before attaching the pressure line and extending the cylinder. The bottom stage area is typically greater than the retract annulus area by a factor of 8 to 10. If the retract port is blocked when extend pressure is applied to the cylinder, the pressure in the retract annulus will be intensified by a factor of 8 or 10. For example, a 4,000 psi setting pressure will produce 40,000 psi of pressure in a blocked retract annulus. This magnitude of pressure will literally rip the threads off the end cap of the cylinder casing.

CONCLUSIONS

Hydraulic roof support systems are used extensively in underground mining for critical roof support in many areas. The performance characteristics of these hydraulic supports need to be fully understood to optimize the use of these hydraulic support systems and to evaluate problems when they occur. A proper understanding of these high pressure systems is also necessary to prevent injury during repair operations.

The following conclusions are made regarding the performance characteristics of hydraulic support systems and their impact on ground control capabilities.

1. Setting forces are reduced whenever the bottom stage is fully extended, which occurs on operating cycles which establish a **new maximum operating height**. The setting force will always equal the pump pressure times the area of the largest stage which is not fully extended. Force reductions of 40 to 50 pct are common for two-stage hydraulic cylinders. Reductions as large as 70 pct are common for three-stage cylinders when both the bottom and middle stages are fully extended.
2. The stiffness of a support controls the development of the support loading in response to the ground movements that cause roof and floor convergence. Several conclusions are made in reference to the stiffness of hydraulic support systems.
   (a) Stiffness is not significantly affected by the setting pressure.
   (b) Generally, stiffness is a nonlinear function of operating height, decreasing exponentially as the height increases. However, in multi-stage cylinders, the stiffness is also dependent on the combination of stage extensions. The same stiffness can occur at different operating heights, and certain combinations of staging can produce greater stiffness at higher heights.
   (c) Stiffness is primarily controlled by the diameter of the hydraulic cylinder with increased stiffness as the diameter of the cylinder increases. In multi-stage cylinders, it is the smallest (diameter) stage that largely controls the stiffness of the support. Higher capacity longwall shields tend to be stiffer due to the use of larger diameter hydraulic cylinders. Two-stage systems should be used whenever possible, since two-stage systems are stiffer than three-stage systems for the same (bottom stage) cylinder size.
3. The supporting force of a longwall shield is reduced by approximately 10 pct each time it yields due to excessive hydraulic pressure which opens the yield valve. Yielding causes an increase in shield stiffness due the reduction in cylinder length.
4. The support loading (both setting forces and a large percentage of the post setting load development) cannot be determined from bottom stage pressure measurements whenever the bottom stage is fully extended.
5. Both internal and external hydraulic leakages will reduce the support capacity to zero under static loading conditions. The time required for complete loss of load carrying capacity depends on the initial loading and the leakage rate, and thereby ranges from a few minutes to a few hours.
6. Observations of the relative positions of the cylinder staging can be used to identify cylinder problems and the cause of hydraulic leakages. One tell-tale sign of internal leakages is when the bottom stage is consistently fully extended. Another sign is when there are several inches of difference in staging on leg cylinders on the same support. Leakages associated 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. 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.

Finally, safety precautions should be made when working with these high pressure hydraulic support systems. The fluid pressure is more than adequate to cause serious bodily harm.

Support structures should be properly stabilized during repair work. Incorrect connection of hydraulic hoses to the cylinder can result in unintentional damage to the hydraulic cylinder and potential injury to the mine worker. A well trained person should be conducting the removal, installation, or repair of hydraulic support systems.

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