Preliminary Design of an Improved Load Measuring Device for Underground Mining Standing Supports

Brandon Stables

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Abstract

Standing support is often used in conjunction with underground retreat mining. Knowledge of the load-displacement behavior of a standing support and loading induced by the mine opening is critical proper support selection. The NIOSH STOP database contains load-displacement laboratory test data for most commonly used standing supports. Hydraulic load cells currently used to measure in-situ loading of standing supports have exhibited leakage under load, producing irregularities within the dataset. An improved hydraulic load cell eliminates leakage and produces more consistent data.
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General Audience Abstract

In retreat mining of a traditional room and pillar or longwall mining operation standing support is utilized. The standing support is comprised over various types of systems, wood timbers, wood cribs, pumpable supports and metal supports. These standing supports help aid in the recovery of the reserves and/or maintain ventilation through the mining excavation. National Institute for Occupational Safety and Health (NIOSH) Support Technology Optimization Program (STOP) has a database of laboratory testing on load displacement used on various standing supports. To relate this laboratory testing to in-situ load of standing support hydraulic load cells have been introduced. The hydraulic load cells design is a thin metal bladder filled with fluid that is placed on the top or bottom of the standing support. These hydraulic load cells have exhibited inconsistencies due to leakage under load, producing irregularities within the dataset. To achieve a reliable dataset on active standing supports it is vital that current load-measuring devices needs to be re-evaluated and redesigned.
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Chapter 1: Introduction

Standing support is often used in conjunction with underground retreat mining. In retreat mining of a traditional room and pillar or longwall mining operation standing support is utilized. The standing support is comprised of various types of systems; wood timbers, wood cribs, pumpable supports and metal supports. These standing support systems can help aid in the recovery of the reserves or maintain ventilation through the mining excavation, or both. Without these various standing support systems in place during retreat mining the areas could experience roof and/or rib failures.

Laboratory testing has been conducted to gain valuable comprehension and load characteristic behaviors of standing supports. As a result, the National Institute for Occupational Safety and Health (NIOSH) Support Technology Optimization Program (STOP) has a database of laboratory testing on load displacement used on various standing supports.

Once a baseline dataset was established by the STOP program of each standing support system underground load-measuring devices were introduced, providing an in-situ load dataset. Hydraulic load-measuring devices are commonly used on standing supports, and the current devices being sourced exhibit irregularities in the dataset due to leakage under load.

This thesis will demonstrate the design concepts of an improved load-measuring device to testing each design concept. The 38th International Conference on Ground Control in Mining, featuring An Improved Load Measuring Device for Underground Mining Standings Supports (Stables, B., Mirabile, B., Westman, E., 2019) compares updated design concepts and testing of several Fluid Filled Load Measure Devices (FLMDs) to hydraulic load-measuring devices currently being manufactured. Detailed evaluation of the preliminary redesigns and the current production models of load-measuring devices for standings supports are examined in Chapter 3. Additional research is performed in order to obtain a more reliable in-situ dataset of standing support systems.
Chapter 2: Literature Review

2.1 - Standing Supports

During early development in underground mining in small tunnels, using only a few hand tools, standing supports weren’t required until geologic features created unsafe work environments. As underground mining expeditions advanced further in the ground seeking minerals, standing support devices would be necessary to maintain passable entries. Standing supports were used as the first roof control products to alleviate the possibility of ground failure or roof fall.

Standing support systems, also known as secondary supports, are added to aid in the primary ground support system. The primary ground supports are installed as mining advancement takes place; this is typically the first type of bolting installed in the mine roof. Most common primary supports are headed rebar bolts, conventional mechanical bolts, combinations bolts, and tensionable point anchor rebar bolts. Primary supports typically are installed into 1 or 1-3/8 in. (25 or 35 mm) diameter drill holes and anchored into the roof strata with a fast setting resin cartridge. These primary support bolts can be either fully or partially grouted, depending on the geological conditions and roof control plan. For the bolt to be considered fully grouted, resin must be encountered within a distance no greater than 1 inch for each foot of bolt length (i.e., for an 8-ft bolt, then the resin should be encountered within 8 inches of the roof line) U.S. Department of Labor. (2013). Each of the primary bolt systems has a specific application requirements depending on the geologic conditions at the time of mining excavation.

The next type of ground support installed in the mining entries is the supplemental roof support. The function of supplemental roof support systems is to prevent the delamination of the roof beam and to support the weight of strata which becomes separated from stable roof structures (Barczak, T.M. and Gearhart, D.F., 1994). Adding a supplemental support system in conjunction with the primary support aids as a backup protection in the possibility of the primary bolting system fails to create a strong roof beam. Supplemental supports are longer than the primary support systems installed to anchor into undisturbed roof strata. These typically consist of the following; non-
tension cable bolts, tensionable cable bolts, fully-grouted cable bolts and combination bolts.

Cable bolts are the most commonly used supplemental support systems installed throughout the mining sector. With the introduction of tensionable cable bolts, this newly developed support system can be used as either primary and/or supplemental supports. In the United States, cable bolts are typically installed in either 1 or 1-3/8 in. (25 or 35 mm) diameter drill holes and, if point anchored only, are utilized with 4 – 5 equivalent feet (1.2 – 1.5 m) of resin (Dakota, D., 2012). Cable bolts permit an expansive amount of horizontal ground movement without shearing compared to other rigid rebar bolting systems used as supplemental supports. Cable bolts provide either elastic or non-elastic characters depending on the application and installation practices.

2.1.1- Standing Supports Review

Mining the smaller entries allowed for the ribs and pillars to maintain the weight needed to support the areas extracted. A pressure arch is developed from the redistribution of the vertical stresses upon development of the roadways (Barczak, 2003). With the invention of larger equipment to help extract the minerals from the Earth, which in turn increased the entry widths. As the entries widen it was a common practice to install standing supports in underground mining applications.

Standing supports have been used from the introduction of mining. Standing support or secondary supports are devices that rest against the floor of the mine and the top portion of the support is installed firmly against the roof of the mine. Wooden timbers were used to support the mine roof before the invention of today’s common roof bolting systems. These standing supports evolved over the decades of mining and technological advancements. Without these standing support developments, many coal reserve extractions would pose severe roof and rib deterioration and safety concerns. Standing supports must yield as the entry closes while maintaining stability and sufficient load carrying capacity to provide control of the immediate roof and maintain a safe travel way in the entry (Barcak, T.M. and Gearhart, D.F., 1995). Standard wooden timbers are still the primary choice of mining operators of secondary support systems today, now mining.
operations have the additional options of engineered timber support, cementitious cribs and steel supports.

These various standing support systems are used in traditional roof and pillar and longwall mining. As these supports are installed for various mining solutions, the standing supports aid in reducing the amount of roof or floor movement to maintain a safe travel way, adhere to ventilation requirements and prevent any roof or rib failure.

### 2.1.2 – Wooden Support

One of the first supports consumed in mining applications and still readily accessible today is the wooden roof to floor support. Wood supports over time have issues with drying out, causing a loose roof to floor support, even if no geological movement within the area has occurred. Cap wedges are needed to firmly install these wood supports due to the irregularities in the mine floor and roof. These wedges allow the wood supports to be tightened again as the drying of the wood occurs. Underground observations and analysis of loading-deformation behaviors of wood cribs indicate that significant displacement occurs before the anticipated capacity can be reached (Chen, J., Mishra, M., Beck, K., Barczak, T., Bower, J., and Huff, C., 2003). If a timber is used for an extended duration rot could develop with an untreated wooden support. As an alternate to standard wood supports, some supports may be pressure treated to prolong their life expectancy.

#### 2.1.2.1 – Timber

The dominant type of roof to floor support is the wood timbers, as wooded areas to obtain these timbers usually is readily available in most mining regions. These wooden timbers consist of cylindrical and square shapes ranging from 152.4 - 203.2 mm (6.0 - 8.0 inch). Wooden timbers have a load bearing capacity of 378 - 1,704 kN (38 - 171 t) at a height of 914.4 mm (36.0 inch). Load bearing capacity is dependent on the length of the wooden timbers. As the length of each wooden timber diameter progressively gets longer
in length, the less each timber’s load bearing capacity can resist. These timbers typically are mixed hardwoods depending on the mine specifications.

2.1.2.2 – Wooden Crib

Another type of wooden roof to floor support system is the wooden crib. These wooden cribs are usually constructed with 152.4 mm (6.0 inch) by 152.4 mm (6.0 inch) wooden timbers. The wooden crib support system consists of square wooden timbers stacked together to make a 4-point crib. To increase the loading stiffness and capacity a 9-point or 16-point crib would be constructed. Usually the more points of contact the crib has the larger the footprint it creates in that area.

For a wooden crib enhanced performance construction the ends of each timber will need to have overhang at least half of the width of the timber. This overhang will increase the strength and stiffness of the wooden crib structure. Wood crib designs that employ parallel to the grain loading or more than two timbers per layer in conventional crib configurations provide the next highest support capacity and stiffness (Barczak, T.M., and Gearhart, D.F., 1994). As load is applied these wooden crib timbers the overhang compresses into the one below creating a locking type of mechanism. Cribs constructed with overhanging timbers provide a 10 - 15 pct. increase in crib resistance (Barczak, T.M., and Gearhart, D.F., 1993).

A locking wooden crib support is just an advanced engineered wooden crib, known as a Link-n-Lock or J-Latch support system. It is comprised of notches cut out towards the ends of each timber, similar to the log house construction method. With the notches it permits the timber to rest entirely on the timber below, allowing for increased support capacity, stability and stiffness. The locking wood cribs are designed for 4 point and 9 point areas of contact and typically 76.2 mm (3.0 inch) x 152.4 mm (6 inch) in a rectangular shape. At 508 mm (20 inch) of displacement these interlocking crib supports can achieve a load capacity of 996 – 2,491 kN (100 – 250 t).
2.1.2.3 – Engineered Timber

Applications of an advanced wooden timber system were introduced to give an alternative timber support; as different adverse conditions were encountered. Wood has been the traditional support construction material, but wood suffers from being too soft (when loaded perpendicular to the grain) or unable to yield sufficiently (when loaded parallel to the grain) (Barczak, 2003). These engineered supports have an increase in stiffness compared to standard wooden round or square timbers used previously.

As the stiffness of these supports increases the installation footprint area of these timbers increases as well. One type of standing support consists of a set of three timbers fastened together. These are secured with a metal rope or band surround the three timbers to create a more rigid support system. Another type of engineered timber has been designed with a built-in yield zone on either end of the wooden timber. This single timber has been cut in a specific engineered design pattern and with three metal bands installed on the ends to control the deformation of the wooden timber. These engineered wooden timbers consist of cylindrical shapes ranging from 177.8 – 304.8 mm (7.0 – 12.0 inch). Engineered wooden timbers have a load bearing capacity of 249 – 2,491 kN (25 – 250 t) at a height of 1,220 mm (48.0 inch).

2.1.3 – Cementitious Cribs Support

These specialized pumptable cylindrical cribs have replaced the conventional wooden timber cribs use in longwall tailgates and bleeder entries. Development in the 1990s, the first major use of pumptable supports systems in U.S. longwall operations was in the support of bleeder entries (Barczak, T.M., Tadolini, S., 2008). Cementitious cribs are cylindrical in shape instead of the traditional wood cribs that are square or rectangle. The cylindrical designed cribs allow greater air ventilation and generate smoother vortexes down the ventilated entries.
2.1.3.1 – Cylindrical Metal Cribs

The cylindrical metal cribs, also known as a “CAN”, consist of a thin wall steel cylindrical container and the container is filled with a cellular concrete material. The manufacturing of this cylindrical metal crib is completed off site including filling these metal cribs with the cellular concrete material, then shipped to the mine location. Once underground these metal walled cribs will require specialized equipment to install. The container can be smooth or similar to a corrugated shell. Wedging is needed on the top and bottom of the cans to make sure it has full surface contact and is level in the vertical direction. The container diameter can range from 457 – 914 mm (18 – 36 inch) and have a support capacity of 648 – 1,644 kN (65 – 165 t).

As the cylindrical metal crib takes weight the cellular concrete will crush, filling all voids in the cylindrical container. Once this has been achieved the metal cylindrical can will begin to crush resulting in a yielding crib. The loading characteristics of the CAN support is an initial stiff elastic response that causes a rapid build-up of load followed by a slight strain-hardening yielding phase (Batchler, T., 2017).

2.1.3.2 – Pumpable Crib

The pumpable roof support is a grout-filled support that is formed in place in the mine entry by pumping a specialized grout into a fabric bag that is hung from the mine roof (Barczak, T.M., Esterhuizen, G., and Dolinar, D.R., 2005). The pumpable cribs consist of the following:

1. An impermeable, fiber reinforced bag.
2. A continuous helix reinforcement wire, high-strength spring steel in the standard bag, and carbon fiber in the cuttable bag.
3. A cementitious fill material, approximately 90 percent water, designed to be pumped extreme distances.
4. An optional internal or external reinforcement layer to provide enhanced deformation capacity (Campoli, A.A., 2015).

The specialized fabric bag can be altered to help with loading characteristics needed for the specific application. By changing the type of internal fabric reinforcement
of wire or rope also by changing the pitch of the fabric reinforcement will alter the 
loading characteristics of these pumpable roof support systems.

A pumpable crib consists of two part mixing system. These can be pumped for 
long distances up to 5,486 m (18,000 ft) down a borehole from the surface location. The 
pumping distance is greatly dependent on vertical head pressure created by the elevation 
difference between the mixing site on the surface and installation site underground. The 
slurry when mixed will gel in less than 30 seconds depending on the application, mixing 
of the two-component slurry mix occurs at the mixing nozzle as it is pumped into the crib 
bags strategically positioned in the mine entry underground. Pumpable cribs usually 
achieve full strength for weeks after being pumped (Zhang, P., Milam, M., Mishra, M., 
Hudak, W.J., and Kimtis, R., 2012). Typical to achieve full strength will take on average 
28 – 56 days depending on the additives included in the crib material mixture. Standard 
pumpable crib diameters are 610 – 762 mm (24 – 30 inch) and have a support capacity of 
1,495 – 2,292 kN (150 – 230 t).

Using pumpable cribs eliminates the use of wedges and blocking material used 
to fill in gaps between the top of the crib and the roof (Barczak, T.M., Tadolini, S., 2004). 
Pumpable cribs bags act as containment devices once fully pumped with the specialized 
cementitious grout and will provide full contact with the roof and floor. With the ability 
to have full contact with the mine roof, at times additional skin control is required in 
these areas; metal or plastic mesh can be installed above these supports.

The pumpable roof supports has the second highest capacity and stiffness, 
compared to the concrete donut crib. The concrete donut crib has the highest support 
capacity and stiffness. They provide a high peak load capacity and a sustained, 
confinement-controlled yield behavior while maintaining stable ground conditions, which 
is essential to underground mining operations (Batchler, T., 2017). The donut crib, when 
it reaches it’s peak load it loses it quickly, due to fracturing of the concrete material 
creating a non-yieldable crib. Whereas, the pumpable crib uses a fiber reinforced bag to 
confine the material as it begins to facture during loading creating a yieldable crib 
support.
2.1.4- Steel Props Support

Floor to roof supports can also consist of steel type supports. These supports are mostly cylindrical in shape with a flat base plate attached to bottom and/or top portion of the steel support. The base plate will help aid in the support by stabilizing it on the roof and floor depending on installation practices. Additionally, the base plate will assist in surface contact area for the steel support in reducing its ability to penetrate the roof or the floor of the mining entry.

Depending on the application the top base plate can be interchanged with several head configurations. As previously mentioned, the top base plate can be flat, and the majority of the time this flat plate will have the ends turned up at each end. Turning the end up at each corner will allow the flat plate to dig into the floor or roof allowing minimum movement in the horizontal direction.

The top plate can be designed to allow for an installation of a steel beam. The steel beam can vary in shape and size dependent on application and design features. Another option available is a yieldable round steel pan top, which as a convex shape that allows yielding before the steel prop reaches maximum load capacity.

2.1.4.1 – Rigid Steel Prop

This application is dependent on the type of steel prop to be used; a rigid system will not allow the prop to yield. This design allows the steel prop to get to high load quickly and is able to maintain high loading until full capacity is reached. These types of steel props will range from 249 – 996 kN (25 – 100 t) load capacity.

Rigid steel props can be designed and manufactured with various installation procedures. One type has an internal pipe that is threaded and the outer pipe has a collar that can be turned. Turning this collar will allow for the extension and contraction in length, length of maximum extension 610 mm (24 inch). Another type of steel prop consists of pulling the inner tube in an upward direction allowing the ceramic “sand” beads to pass by filling the outer tube. Once the sand is in the outer tube it can only be extended never retracted.
2.1.4.2 – Yieldable Steel Prop

Movement allowing the prop to contract during loading of the steel prop is considered a yielding prop. After the steel prop is installed firmly, and once the roof and/or floor begin to move in the vertical direction, then the prop begins to load. As with the rigid props, the yieldable props also load quickly as they reach the design loading parameter of 249 – 996 kN (25 – 100 t). Once the props achieves maximum designed loading the prop will yield allowing movement in the roof and/or floor, without fully compromising the strength of the steel prop.

A yielding prop can be manufactured in various designs dependent on the application. A round metal dish profile can be installed on the top of the prop to allow for vertical movement. Prop designs that are installed with water, or even air pressure, have the capability of yielding at set parameters.

2.2 – Applications of Standing Support Designs Methods

Standing supports had been introduced to mining applications before primary roof support systems have become normal operating practice. These supports in the 1800’s to early 1900’s consisted of wooden timbers to help maintain the entries width and to support the unstable strata above the mining entries. Today it is common to see the introduction of a variety of standing supports to aid in the control of roof movement as third line of defense.

Primary ground support systems are installed as these mining entries advance. These primary ground supports consist of different types of roof bolts at various lengths held in place with a resin cartridge. Typical lengths for primary support systems range from 0.91 meters (3.00 feet) to 2.44 meter (8.00 feet). Primary supports typically are installed into a 1 or 1-3/8 in. (25 or 35 mm) diameter boreholes, to allow for the correct annulus of resin ratio. The resin cartridges act as an anchor for the bolts installed and provides strength across the entry constructing a high strength beam. Headed bars can be installed with a variety of hardware or with a resin cartridge, making them extremely versatile and applicable in many situations (Walker, R.C., Slatter, M., 2009). The
manufacturing process of these various bolting systems must comply with regulatory standards as addressed in the ASTM F432-19, American Society for Testing and Materials standard specification for roof and rock bolts.

The resin cartridge contains two compartments separated by a sealed polyester film to prevent exposure until the cartridge has been mixed by the rotation of the bolting machine. One compartment contains the resin and the other compartment contains the catalyst. The gel time of these resin cartridges is a rapid set time depending on the application. The gel time can range from just a few seconds to minutes which allows ample time for the operator to fully install the primary ground support in the drill hole.

Supplemental supports systems consisted of various types of ground control systems, but most commonly utilized currently is cable bolts. Cable bolts were introduced to the U.S. mining industry in 1970 as a method to reinforce ground prior to mining (Tadolini, S.C., and Koch, R.L., 1993). Cable bolts are based on a 7-strand high-strength cable, different diameters for greater load bearing capacity. Standard lengths for supplemental supports range from 2.44 m (8.00 feet) to 6.10 m (20.00 feet) also have a diameter of 15.24 mm (0.60 inch) and 17.78 mm (0.70 inch). Furthermore these cables come in a variety of styles depending on the application and ground controls requirements: non-tension cable bolts, post-tension cables bolts, tensionable cable bolts (can be installed for primary or supplemental roof support) and fully grouted cable bolts. Each cable bolt is installed with a type of resin cartridge or a pumpable grout to anchor into the strata. Typically, the resin cartridge installed with the cable bolts has a thinner viscosity and polyester film to allow ease of insertion into the borehole especially for lengthier cables due to their tendency to flex before fully installed. The anchor point for cable bolts is above the primary support anchor horizon. The cables’ characteristics provide a large amount of deformation and resistance to shear at a high degree of loading and ultimate tensile strength (Tadolini, S.C., Tinsley, J. and McDonnell, J.P., 2012). The flexibility of the cable bolts compared to a rigid bar system can aid in the ability to resist horizontal movement within the geology of the mine roof without exceeding ultimate shear strength. A rigid rebar system either installed with only resin or mechanically anchored resin assisted will merely resist horizontal roof movement to a degree, with excessive horizontal movement within the immediate roof the ridged bolt will shear
within the borehole. Shearing of the bolt has occurred below the resin encapsulation zone initiating the bolt to drop or be ejected out of the borehole.

Secondary ground support systems are a form of standing supports. Standing supports assist in controlling the movement of the roof if delamination occurs in the mining entries. These secondary ground supports systems are floor to roof supports consisting of wooden timber supports, cementitious crib supports and steel prop supports. While secondary supports provide the last means of support in the event there is roof failure above the bolted horizon, the primary function of the secondary support system is to assist the primary support system in maintaining the integrity of the immediate roof (Mucho, T.P., Barczak, T.M., and Dolinar, D.R., 1999). Secondary support systems placement in the mining entries should take place before the strata meets critical deformation. Once the strata failure occurs to a point where the primary and supplemental supports have reached their support capacity, the secondary standing supports may need to endure the peak loading of the ground strata in that given area.

2.2.1 – Standing Support Designs Methods

Support technologies are ever evolving to achieve a theoretical load-displacement relationship. Support technologies in terms of performance can be classified into four basic types as illustrated in Figure 1: (1) non-yielding, (2) constant yielding, (3) load-increasing (strain hardening) yielding, (4) load-shedding (strain softening) yielding (Barczak, T.M., 1995).
The non-yielding support represents the initial maximum load is reached very quickly but sheds its support load once maximum load is reached. Load shedding involves reaching maximum support load quickly, followed by the load beginning to shed slowly, allowing for additional displacement as the load supporting capacity drops. Constant yielding begins with gradual load increase until maximum support capacity is reached, thereafter the floor to roof supports maintain maximum support capacity while the displacement of the support remains constant. Load increasing can be described as the support continuing to increase in load capacity, thereby allowing this floor to roof support to maintain a fairly upward uniform trend of displacement.

Figure 1: Ideal load versus displacement (after Barczak et al., 2005)
Table 1: Load Response Curve

<table>
<thead>
<tr>
<th>Load-Response Curve</th>
<th>Support Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Yielding</td>
<td>Rigid Prop</td>
</tr>
<tr>
<td>Constant Yielding</td>
<td>Cylindrical Metal Crib</td>
</tr>
<tr>
<td>Load Shedding</td>
<td>Pumpable Crib</td>
</tr>
<tr>
<td>Load Increasing</td>
<td>Wooden Crib</td>
</tr>
</tbody>
</table>

The comparison of the floor to roof standing support displacement characteristics is shown in Table 1. The rigid metal prop along with the wooden timber, reaches its high capacity load and stiffness quickly but rapidly loses capacity once peak load capacity is reached, making these types of secondary standing supports a non-yielding support system. Cylindrical metal crib and yieldable prop support systems are considered constant yielding because when these supports reach peak capacity they will continue to yield. As the cylindrical metal crib skin along with the cementitious grout inside the metal crib continues to crush, a constant yielding support system is created until the metal skin tears. At this point the support sheds its load. As with the yieldable prop, the cylindrical metal crib prop is designed to take a high capacity load then begin to yield while maintaining a stable support capacity. The pumpable crib, which is filled with a cementitious product inside a reinforced fabric bag, is classified as a load shedding support system. As the pumpable crib increases in support capacity it will, at various stages, shed load by crushing the cementitious product and the reinforced fabric bag will expand. As the pumpable crib reinforced fabric bag confines the material inside its cavity the pumpable crib will gain strength again until it sheds load once again. These sequences of shedding load and gaining strength will continue to occur repeatedly until the fabric bag rips releasing the cementitious product. The wood crib is the softest support system, but increases its load carrying capacity as it yields (Barczak, T.M., Esterhuizen, G., and Dolinar, D.R., 2005).

2.2.2 – Optimizing Standing Support Designs

Secondary supports also referred to as standing supports and/or roof to floor supports are installed in the event of the failure of the primary and secondary supports
systems installed in the mine roof. These failures occur when the rock segments detached from their current state of in-situ. Standing supports should be installed early enough and develop sufficient capacity to bring deformation of the ground into equilibrium before a critical deformation is reached that leads to a detached block condition, at which point the standing support will be required to carry the entire dead weight of the detached rock mass to prevent a roof fall from occurring (Mucho, T.P., Barczak, T.M., and Dolinar, D.R., 1999). Secondary supports are installed in advance of this critical deformation failure and at numerous instances after the roof primary or supplemental support systems failure has originated. Installing a secondary support system will assist in controlling any additional convergence that may occur after delamination of the roof strata.

To help assist the efforts to control the convergence of the mine entries with secondary support, the National Institute for Occupational Safety and Health (NIOSH) has developed a program to facilitate and evaluate the various types of secondary support systems, Support Technology Optimization Program (STOP). This STOP system assists mining companies, regulatory agencies along with manufacturers of secondary support systems by determining the performance characteristics of each support tested.

Testing is conducted on the Mine Roof Simulator (MRS) at the NIOSH Testing Laboratory. NIOSH’s Mine Roof Simulator (MRS) load frame was designed specifically to determine the load-displacement performance characteristics of roof support system (Batchler, T.J., 2017). The NIOSH Mine Roof Simulator has a 3,000-kip vertical load and 24-inch displacement capacity, which has facilitated in-depth analysis of complex multi-material support technologies like the pumpable crib (Campoli, A.A., 2015).

The STOP program was derived from a previous program that exclusively focused on wooden crib materials, Wood Crib Performance Model. This was a basic program for determining standard installation support capacity practices, support capacities for various standing support configurations, then to match support capacities attained by STOP program to a user defined load and convergence. To increase the performance and information gathered the STOP program was revised to introduce further functionality to determine more in depth knowledge of these different supports that were being introduced to the mining industry. The features added to the STOP system include: selection from a data base of currently available standing roof support
systems for evaluation, synopsis of pertinent design and installation criteria for each support system, description of the performance characteristics including photographs of the supports loading profile showing the condition of the support as it deforms, name and phone numbers for the support manufacturers, ground reaction curve support design criteria where the laboratory support performance can be matched to a curve corresponding to the ground behavior as opposed to a single (load and convergence) data point as was done in the wood crib model, enhanced optimization algorithms that determine the support design which is most efficient for the user-specified support installation requirements, or the installation requirements for user-defined support load density and convergence requirements, material handling and cost information for each support, and graphical displays of the support system capability (Barczak, T.M., 2000).

With the development of new support systems with the wooden cribs as the baseline secondary support, the STOP program has now six categories of various supports. The classification of these six supports is as follows:

1. Conventional wood (crib) support
2. Engineered timber supports
3. Conventional concrete crib support
4. Yieldable concrete supports
5. Steel supports
6. Additional supports

As new technologies arise and innovative standing supports are introduced they will fall into one of these categories.

With the advances of the STOP program an additional critical feature that was introduced into this program, the Ground Reaction Curve. The Ground Reaction Curve is the most powerful design option in that it is a measure of the support and strata interaction, which if known, allows one to design a support system which will limit the convergence in the mine opening to a designated level, and hence ensure stability of the mine entry based on in-mine observation of ground behavior (Barczak, T.M., 2001).
2.3 – **Ground Response Curve**

The concept of a ground response curve was originally developed for the tunneling industry where the timing and method of ground support is determined by monitoring the support pressure and excavation convergence during construction (Brown, E.T., Bray, J.W. Ladanyi, B. and Hoek, E., 1983). The goal of the ground response curve is to optimize the standings support to control the convergence of mine roof within a particular boundary to prevent mass roof failure. The ground reaction will depend on the rock mass characteristics, loading conditions and the support resistance (Dolinar, D., Barczak, T.M., and Gurley, H., 2009).

The ground response curve is a plot support pressure or load density versus convergence for an opening in a rock mass under a specific set of loading conditions (Mirabile, B. 2018). Figure 2 shows a conceptual ground response curve. Point A represents the initial stress level in the rock mass before any excavation has occurred and has no convergence at this stage. As the support pressure is reduced, the excavation boundaries converge and the pressure required to prevent further convergence reduces as arching and the self supporting capacity of the ground develops at point B (Barczak, T.M., Esterhuizen, G., Ellenberger, J., and Zhang, P., 2008). As the curve represents point C, in this stress point location the resistance has increased to a self-supporting capacity but also allows for permanent deformation of the rock mass. The failure of the strata has caused a dead weight load at point D.

![Figure 2: Conceptual ground response curve (after Barczak et al., 2005)](image)
On the ground response curve there are three segments to the curve that represent different stages of excavation and support loading conditions. The segment A-B illustrates the initial excavation of the mining cavity. As the material is excavated creating a tunneling affect, the rock mass will begin its elastic stage followed by segment B-C convergence of the mining out cavity with no support installed. At this segment the rock mass deforms permanently. The next segment C-D is the rock mass failure.

The uncontrollable convergence happens within and past the first segment of the ground reaction curve A-B observed in Figure 3. The movement of the ground strata occurs during initial excavation of the mining entry. Increasing the load capacity of the standing supports in this area typically will not have a significant affect on the uncontrollable convergence. The ground reaction curve shows that standing supports must survive the initial uncontrollable convergence and should retain sufficient capacity to exceed the required support line (Barczak, T.M., Esterhuizen, G., and Dolinar, D.R., 2005). This uncontrollable convergence is also seen as the curve moves in the upward trend between C-D segment.

![Figure 3: Conceptual ground response curve with convergence (after Barczak et al., 2005)](image)

Uncontrollable convergence will emerge once the mine excavation has occurred until the standings supports are installed in the mine opening. After initial installation of the standing support in the entry and before the ground reaction curve reaches point B shown in Figure 3, the strata in that zone has already seen its initial convergence. As the convergence continues to point B the standings support load increases in relationship to
the supports’ stiffness until it reaches its ultimate performance characteristics of that particular standing support installed. Once the standing support reaches its peak support capacity then the support will begin to yield until the point B is reached. To maintain the entry opening, standings supports capacities will need to be higher than point C on ground reaction curve.

2.3.1 Ground Response Curve Support Design

The design of standing supports requires knowledge of the loads that the ground will impose on the supports and the roof-to-floor convergence that will occur (Esterhuizen, G.S., and Barczak, T.M., 2009). The ground reaction curve provides assistance in determining the support system required for a particular mining open cavity. These design parameters can be calculated based on previous measurements acquired. These measurements include convergence and load capacity of a standing support. Load density is the tons per square foot that a standing support is capable of supporting, illustrated in equation (1). The number of supports is referring to the number of the standing supports within the given area to calculate the load density. Load of supports is the capacity per standing support represented in tons. Width of entry is width of the entry measured in feet. Length of standing supports is the linear length of the entry where the standing supports are located in feet or area of support coverage.

\[
\text{Load Density} = \frac{\text{Number of Supports} \times \text{Load of Supports}}{\text{Width of Entry} \times \text{Length of Spacing of Standing Support} \text{ (Support Coverage Area)}}
\]  

(1)

For a single row of standing supports introduced in the mining entry the following equation (2) would be applied. Center to center spacing refers to the amount in feet between the centers of the standing supports.

\[
\text{Load Density} = \frac{\text{Load of Supports}}{\text{Center to Center Spacing} \times \text{Width of Entry}}
\]  

(2)
These load density data points are then used to establish a ground reaction curve for the given area. The next step of creating design parameters for the standing support is to determine center-to-center spacing. Spacing is the center-to-center in feet of the standing supports represented by equation (3). *Capacity* is the individual standings support in tons at a specific displacement equal to the design criteria. Spacing of these supports is a critical design parameter to consider; typically the spacing should not exceed half the entry width. If standing supports are spaced too far apart, this design feature could be the foundation of premature failure of the roof strata and could have roof related issues into the future.

\[
\text{Spacing} = \frac{\text{Capacity}}{\text{Load Density} \times \text{Entry Width}}
\]  

These design methods assist in optimizing the standing support pattern to maintain adequate support capacity without major failure. The *ground response curve safety factor* is important to understand in determining a margin of safety for standing support design to overcome the critical convergence, illustrated in equation (4). In order to make equivalent comparisons of alternative support systems, a safety factor can be quantified by comparing the design support load density to the *minimal acceptable support load density* which will representative of the maximum allowable (critical) convergence (Mucho, T.P., Barczak, T.M., and Dolinar, D.R., 1999).

\[
\text{Ground Response Curve Safety Factor} = \frac{\text{Design Load Density}}{\text{Minimal Acceptable Load Density}}
\]  

When designing the support systems a safety factor of the support must be in place to prevent a failure within the mine roof. When a safety factor of 1 is calculated it indicates that there is no reserve capacity for the standing support available. A safety factor of 2 indicates the support capacity is at 50 percent per the maximum load the standing support can achieve. As with a safety factor of 1 or below the secondary support system is too soft, hence this reaction would cause roof failure to occur or the area that is being supported deteriorates over time again causing premature roof failure.
Also a secondary support system designed can also be too stiff. Stiffness of a support is how quickly the support can reach its loading capacity versus the convergence. A stiff system would allow the supports to be stronger than the strata around the support and little or no convergence within the support. Once this happens the stiff support will puncture the roof then damage the roofs integrity then pose the potential for roof failure. Additionally the stiff support could puncture a soft floor, causing floor convergence around the supports making the entry size smaller without inducing loading on the secondary supports. Floor heave also is likely to have elements of displacement-controlled activity as the overburden forces acting on the pillar are transferred into the floor, again creating both vertical and horizontal stress changes in the immediate floor of the mine entry (Barczak, T. M., 2003).

Displacement controlled loading is a support that will maintain support and convergence capacity through the uncontrollable convergence shown in Figure 3. As these secondary supports display indications of convergence the supports will maintain their integrity without damaging the roof or floor.

Load controlled support system will be a stiff secondary support system. Convergence of the roof and floor would have to take place before the stiff support would reach its peak capacity. A stiff crib system will attract a large portion of the abutment load, possibly causing the cribs to fail before the longwall can safely mine past the area. Conversely, a soft crib system will attract less abutment load but may provide insufficient support to the immediate and main roofs, potentially causing the primary and secondary bolting systems to fail and the roof to fall before the longwall can safely move past the crib supports (Tadolini, S., Barczak, T.M., and Zhang, Y., 2003). Again with a stiff secondary support system the possibility of roof and floor punctures could occur causing roof failure.

Another option to help assistance in determining high stress areas of a mine is to create a stress map. Stress mapping is a method of visually recognizing horizontal stress influences and determining the principal stress directions based on simple measurements of directional underground failure phenomena, such as cutters, tensile fractures, vertical bolt hole offsets, etc. (Hasenfus, G.J., and Su, D.W.H., 2006). High stress areas can be affected by geological features acting on the mine roof in complex combinations.
Overburden and tectonic stresses, near-seam lithology and structure, mine geometry and development cycle, and ground support techniques may all interact to influence the stability or instability of the mine opening (Mark, C. 1998). By taking the information collected from the visual cues of potential hazards, overlay and underlay maps, topography maps, and including the ground response curve information an accurate stress map can be projected.

Ground response curve is unique for each mining application traditionally. The geological features that are present in the mining area, width of the entry and even the intersections due its large area of span will produce a different ground response curve. Intersection designs can have a variety of configurations, depending on the crosscut leading from the intersection will change the area of span. Increased in supplemental and secondary supports is common practice in these large span creating increased loading conditions. Hence the key to optimizing the support utilization is to prevent convergence beyond the peak loading capacity from occurring in areas where critical roof support is needed (Barczak, T.M., Chen, J., Bower, J., 2003). Enhanced secondary supports are more prevalent in the intersection compared to headings and crosscuts throughout the mining section conventionally.

2.4 – Load Measuring Devices

In order for engineers to determine appropriate and safe pillar-entry designs they must have specific data from the mining seam to create stable working environment of the geological conditions to be encountered. In-situ stress distribution, pillar stability, geological and mechanical properties of the surrounding strata entry width, and roof supporting methods may altogether play a very important role in entry stability (Hart, W.M., Chen, J., Peng, S.S., 1995). To gather this information in the underground environment can be especially challenging. A monitoring system is necessary to aid in determining the factors of the geological deformation conditions after extraction of the reserve within the entry and crosscuts.
2.4.1 Objective of Load Measuring Devices

Several diverse types of load-measuring devices were used in different researches in the past. When determining which load-measuring device is suitable for the particular scenario the unit needs to be a least a portable unit and a unit that can be disconnected from the main data logger by sacrificing itself to the unsafe conditions not allowing human travel inby these areas to retrieve the load-measuring device. Also an installation layout of these devices must be considered, safety considerations if the unit will need to be intrinsically approved and manpower requirements to install the units at the various data collection sites.

One method for a load-measuring device has evolved from a pre-stressing device. A pre-stressing device is positioned at the one end of a standings support, it is filled with air, water, oil or grout so it can inflate to act as active support. Standings or secondary supports are typically a passive roof support system. The active roof loading provided by pre-stressing closes separations in the roof and increases frictional restraint along bedding, joints, and other fracture planes, thereby enhancing beam building (Barczak, T.M., Tadolini, S. (2004). Before pre-stressing of standing supports, primary roof supports consisting of a tensionable roof bolting system was common practice. Tensionable roof bolting systems provide a clamping force to aid in delamination of immediate roof, causing a decrease of adverse conditions by maintaining a strong geological beam of mine roof.

2.4.2 Types of Pre-Stressing Units

The most common type of pre-stressing device used in the earliest of mining excavation and is still commonly installed daily is wooden wedges. The wooden wedge typically is installed in conjunction with standings supports, to help support and secure them in position with frictional force. Wooden wedges are driven into the open spaces above and below the standing supports. These wedges produce an average of 19-39 kN (2-4 ton) of pre-stressing force.

Another type of pre-stressing device that was introduced was mechanical pre-stressing. This device is installed above the standing support and is actually similar to a scissor screw jack design. To expand the plates of the mechanical pre-stressing device a
threaded screw has the capability to be torqued up to 406 N-m (300 ft-lbs) to produce a maximum load of 108 kN (11 ton) of pre-stress. These are not typically installed due to the limitation factors of the placement on top of specific standing supports. The standing support needs to be significantly shorter than mine extraction height to allow for the mechanical pre-stressing device to be installed above the standing support at that particular location. Additionally if the standing supports begin to alter their vertical stance due to horizontal loading these mechanical pre-stressing devices become unstable and unsafe.

Air filled rubber bladders were used in the early 1980’s mostly by South African mines. The bags were positioned at the top of the standing supports and inflated to pre-stress the support before driving the wooden wedges into place. An advantage of the air filled rubber bladders was that the air can expelled from the bladder and then these bladders could be reused at a different locations.

Grout filled bags is a pre-stressing device that was introduced in the 1990 in South Africa. The grout filled bag is constructed of a woven polypropylene that is placed above the standing support, then a chemical grout is pumped into the bag generating up to 0.4 MPa (60 psi) while creating a load force of 785 kN (80 ton). The same company, but within the United States created a very similar product but with a load pre-stressing force of 98 kN (10 ton). This new chemical grout develops a creep potential, causing a deficiency of 49 kN (5 ton) pre-stress force. Creep occurs commonly due to the drying of the engineered wooden standing support manufactured for this system. These grout filled bags are most commonly installed as a pre-stressing device in underground mining.

Water based inflated steel diaphragm is a pre-stressing device that uses water pressure to inflate a steel bladder to add a pre-stress load to the standing supports. The use of inflatable steel diaphragms to pre-load mine props was first tried at Winkelhaak Gold Mine in South Africa in 1978 (Barczak, T.M., Tadolini, S., 2004). These steel diaphragm pre-stressing devices allow water pressure to inflate steel diaphragm to pre-stress the standing support. Since water is readily available at the mine sites this helped promote installation of these water-based pre-stressing devices.
2.4.3 Characteristics of Water Based Pre-Stressing Devices

Water based pre-stressing devices are designed in various design styles and shapes depending on the application. The shapes can range from rectangle, square, round, triangle or any other basic shape for that particular standings support design. These devices are based on a steel diaphragm that is inflated with water to create force acting on the standing support while applying load to the roof and floor. These pre-stressing devices are most commonly used in the association of wooden props or engineered props. They are not designed exclusively for wooden support applications; other options include steel props and cementitious crib standing supports. With wooden standing supports creep occurs due to drying out of the wood, these water based pre-stressing units then could be injected with additional water to maintain a designed pre-stress load adequate for the mining conditions present in that area.

For wooden timber or steel prop standing supports the most common type of pre-stressing device is designed in a cap shape (also known as a Jackpot) so it can be installed over the top of the support as shown in Figure 4. The shape and design limitations of the cap make this design ideal for wooden timber and metal prop standing supports. The cap shape contains a round thin metal diaphragm comprised of thicker area protruding down 50.8 mm (2.0 inch) and 19.95 mm (0.75 inch) wide around the perimeter of the cap style pre-stressing device. Its shape is exclusively cylindrical ranging from 127–254 mm (5–10 inch) in diameter.

![Figure 4: Jackpot shape](image)

The thicker edges protruding down the Jackpots design allow the sides of the cap to securely sit atop of the round standings support as illustrated in Figure 5. As this diaphragm is inflated with water the metal membrane allows for expansion, filling in the gap between the standings support and the mine roof. As additional water pressure is applied the device will apply a pre-stress load on the standing support.
To inflate the cap pre-stressing devices a hand pump, pneumatic powered pump, hydraulic pump or mine water line pressure can be used based on the pre-stress design load requirements. Typically these Jackpots are filled to 1.7–13.8 MPa (250–2000 psi) with a resulting pre-stressing load ranging from 44–533 kN (5–60 ton). A minimum water pressure is required of 0.7 MPa (100 psi) to inflate these Jackpots, at this lower pressure will only fill in the gap between the standing support and the mine roof. These cap pre-stressing devices has an effective expansion capacity range of 76–102 mm (3–4 inch).

To pre-stress wooden or cementitious cribs a larger device is required for the increased coverage area of these standings supports. An industry term defined for this type of pre-stressing device is called a JackPack observed in Figure 6. These water based pre-stressing devices are constructed of two pieces of sheet metal ranging from 12–18 gauge, the perimeter is seamed welded to create an air tight enclosed diaphragm. The design shapes vary from round, triangle, rectangle and square depending on the type of standings support configuration.
Generally these Jack Packs are filled to 0.7–2.4 MPa (10–350 psi) with a resulting pre-stressing load ranging from 50–1,245 Kn (5–125 ton). These Jack Pack pre-stressing devices have an effected expansion capacity of 25.4–304.8 mm (1–12 inch). As these devices reach maximum expansion capacity folds begin to appear in the metal diaphragm, to assist in the reduction of potential metal folds typically a 152.4 mm (6 inch) expansion thickness in optimal. As these folds get severe by excessive expansion of the metal skins it causes potential locations where the diaphragm could rupture. To assist in a preventative failure due folds within the metal skin diaphragm a pressure release valve is installed at a setting 1.7–2.4 MPa (250–350 psi). Another method to reduce the potential of metal fold failure is to size the Jackpack according to the size of the standing support. When the JackPack extends beyond the borders of the standings support surface area this protrusion will increase the likelihood of metal diaphragm skin folds to occur when pre-stressing the support. Placement of these water based pre-stressing devices can be installed at the bottom or top of crib standing supports, normally installed on the top of the standing support. When installed at the bottom of the standing support as the metal diaphragm is inflated the standing support may not be vertically plum due to the distending of the metal skins, then cause premature failure of the load capacity.

Pre-stressing the standing supports with the Jackpacks will create a variation of preload for the same internal pressure introduced to the metal diaphragm. As the metal diaphragm skin inflates it tends to create a curvature type of shape during the expansion, as shown in Figure 6. When the inflation pressure increases along with the curvature of the metal skins less surface contact area is concentrated on the mine roof and the standing support. For a given inflation thickness, equivalent to the gap between the support and the mine roof, the preload will increase proportionally with an increase in the inflation.
pressure (Barczak, T.M., and Tadolini, S., 2004). When calculating the pre-stress load acting on the standing support, the contact area will be smaller compared to the actual size of the JackPack due to direct contact when inflated.

Fitment size of the JackPack and/or jackpot closely as possible to the size and shape of the standing support will assist in maximizing the contact area when the pre-stressing unit is inflated. If an oversized pre-stressing device is installed it will provide a higher preload for that particular inflation pressure and also provide high yield load for the same yield pressure. This is true until a fold happens within the metal diaphragm skin, which could cause premature rupture of the pre-stressing units. To help maximize the contact area for a particular standings support, a smooth top surface would meet this satisfactory condition, whereas with wooden cribs and locking type of wood cribs the top portion of the standing support would require additional blocking or cribbing to create this full smooth surface. On cementitious cribs these pre-stressing devices are installed between two pieces of water resistant plywood to create a full contact surface area.

2.4.4 Transitioning from Pre-Stressed Device to Load Measuring Device

Traditionally the pre-stressing devices were to increase the load of the standing supports by controlling the amount of movement that occurs in the immediate mine roof. Whereas accustomed wood blocking and wedging would only allow limited amount of pre-stress force on the standing supports. These hydraulically pressured devices increase loading of the standing support is superior to the pre-stress load that could be accomplished by conventional wood blocking and wedges.

Installation of pre-stressing devices could eliminate wood blocking and wedging above the standing supports, reduced the amount of wood needed and lessen amount of transportation costs associated with handling of bulky wood products. These hydraulic pre-stressing devices create a full surface contact area between the mine roofline and the surface area of the cribs. As the diaphragms are inflated the thin metal outer skin will contour to the unevenness of the mine roof allowing for additional surface interaction than wood blocking could provide. The primary focus on pre-stressing standing supports include: (1) increase overall stiffness of the roof support, for example, by “closing gaps” in multi-piece units such as timber cribbing, (2) closing gaps in the immediate roof.
structure to enhance beam building, much the same way as pre-tensioning roof bolts, (3) securing the supports to offset timber shrinkage, creep, or any other issue that may cause the support to loose contact with the mine roof prior to any roof loading (Barczak, T.M., and Tadolini, S., 2004).

To introduce a new objective of these pre-stressing devices a design concept of monitoring the loading effects of these standing supports was introduced to create a ground response curve and to understand load displacement in-situ characteristics. As mentioned previously the ground response curve is a plot support pressure or load density versus convergence for an opening in a rock mass under a specific set of loading conditions (Mirabile, B., 2018). The support characteristics can be determined through laboratory tests conducted in such facilities as the Mine Roof Simulator (MRS) (Dolinar, D., 2010). To maintain a safe and effective stability factor of the mine entry a known loading conditions is needed to help predict the loading conditions the standing supports may possibly encounter. In general, the stability of an underground opening mainly depends on the stability of its individual members such as roof, ribs, and floor, while the stability of each individual member is in turn affected by its physical and mechanical properties as well as its internal and external loading conditions (Chen, J., Mishra., M., Beck, K., Barczak, T., Bower, J., and Huff, C., 2003).

Numerical modeling develops a completed ground response curve from the data retrieved from the loading conditions of the pre-stressing devices, immediate mine roof, floor properties and mine layout. The infinite element program used to input this data retrieved from the monitoring the load characteristics from the pre-stressing devices will create a ground response curve in a program known as FLAC. Fast Lagrangian Analysis of Continua, the numerical modeling software for advance geotechnical analysis of soil, rock, groundwater, and ground supports in two dimensions (ITASCA Consulting Group, Inc., 2020).

### 2.4.5 Testing Concept of Load Measuring Device

These pre-stressing devices can be installed in conjunction with standing supports to monitor the results of roof loading as mining occurs, but limited to adjacent panels and/or as the longwall approaches these monitored areas. These pre-stressing devices are
installed with a predetermined pre-stress pressure to fill the gaps between the standing supports and the mine roof, without creating a pre-stressing force on the standing supports. Instead of a pre-stressing device, these devices will now be referenced as hydraulic load-measuring devices since these will be monitoring loading conditions. A dial gauge or a digital pressure transducer could be installed through one of the ports of the pre-stressing device to monitor loading behavior of the standing supports. Information collected will help determine the effectiveness of the primary, supplemental and secondary supports stiffness.

Using gathered instrumentation of the standing supports, the Jack Packs can be installed with a pressure transducer to measure the supports loading. Typically potentiometers are also installed on the same standing supports to measure displacement. To measure the convergence of roof-to-floor, wire potentiometers are mounted to the primary support bearing plate and anchored into the floor of the mine entry adjacent to the standing support.

### 2.4.5.1 Case Study of Loading Measuring Device

A set of testing was conducted previously by (Dolinar, D. 2010) at two different testing site locations within the same mining seam. Both testing sites were on the tailgate entry of a three-entry longwall panel. The standing support at both Site A and B consisted of a cylindrical metal cribs pumped with a cementitious grout mix also known as a (CAN).

Site A represents the longwall panel entry mid pillar and with another testing area located at the intersection of entry. Mine test site overburden depth of 457 m (1,500 ft) and mining entry height ranging between 2.5-3 m (8-10 ft). The pillars spacing was 27 x 15 m (90 x 50 ft), the standing supports layout design and spacing center-to-center was 2.4-2.7 m (8-9 ft) as shown in Figure 7-8.
As the longwall face passed the instrumented area at Site A, this was the area the Jackpacks were installed on top of the standing supports. The instrumented devices were able to track loading as the face approached and passed Site A location. At the midpoint pillar instrumentation area the load-measuring device showed an average 249 kN (25 ton) while the intersection monitoring location averaged 658 kN (66 ton). As noted by Dolinar the load increased rapidly as the longwall face approached, but once it passed the location of the Jackpack the load continued to increase, but at significantly slower rate.
The testing site at Site B represents the longwall panel entry mid pillar and another testing area located at the intersection of gate road. Mine test site has an overburden depth of 232 m (760 ft) and mining entry height averaging 2.7 m (9 ft). The pillars spacing was 27 x 27 m (90 x 90 ft) and the standing supports layout design and spacing center-to-center was 2.4-2.7 m (8-9 ft) as shown in Figure 9-10.

![Figure 9: Site layout of instrumentation mid-pillar Site B (after Dolinar, 2010)](image)

![Figure 10: Site layout of instrumentation intersection Site B (after Dolinar, 2010)](image)

Results from the Jackpacks installed at Site B over the standing supports indicated that after the first longwall panel was extracted the midpoint site reached 369 kN (37
ton), then the intersection load measurement of 598 kN (60 ton) occurred. There was an initial rapid increase in the load development followed by a leveling off, and in 6 of the 10 supports, load shedding occurred (Dolinar, D., 2010).

Both testing sites at Site A and Site B also measured the average roof to floor convergence of the mining entry with the installation of the potentiometer. This convergence measurement allowed (Dolinar) to define the displacement of the mine roof and the potential for floor heave to have occurred. Additionally, with the Jackpacks installed above the standing support not only can it be used as a pre-stressing device, with this evidence the units can be used to measure loading of standing supports. With the knowledge of the location of the active mining versus the loading of the standings supports results can indicate side abutment loading, load shedding, yielding and eccentric loading. During the study the abutment loading was attributed to the support loads developed after the longwall face had passed the test sites. Load shedding yielded the results, the standing support reached a peak load of 658 kN (66 ton) then rebounded back to 329 kN (33 ton). After review of several of the standings supports at test sites indicated eccentric loading which was caused by floor heaving therefore creating the supports to be slanted in the vertical direction.

**2.4.5.2 Case Study of Load Measuring Device in Longwall #2 Entry**

Instrumentation of the longwall gate road in the #2 entry was conducted in the Pittsburgh No. 8 seam. The testing sites average overburden ranged from 244 m (800 ft) to 274 m (900 ft). This panel consisted of a 3-entry gate road with an average width of 4.9 m (16 ft). For this case study that was conducted by (Mirabile), involved four different supports configurations. The pillar spacing was 30.5 x 51.2 m (100 x 168 ft) for all testing locations, the intersections were developed at 60 degrees compared to the 90 degrees in the first case study of Site A.

The first area that was instrumented with monitoring devices consisted of 0.9 m (36 inch) interlocking wooden cribs (Link-n-Lok) with a center-to-center spacing of 2.4 m (8 ft) as shown in Figure 11. The second testing area was comprised of a double row of the interlocking wooden cribs with a center-to-center spacing of 2.4 m (8ft) and 1.2 m (4
ft) between each row as illustrated in Figure 12. The third area was a double row of 0.8 m (30 inch) diameter cementitious pumpable cribs with center-to-center spacing of 2.4 m (8 ft) and 1.2 m (4 ft) between each row in similar approach as second testing area layout. The fourth area testing site had the same spacing pattern at the first area (center-to-center spacing of 2.4 m (8 ft)), but instead of interlocking wooden cribs 0.8 m (30 inch) diameter cementitious pumpable cribs were installed in the #2 entry. Basic configuration of these four test areas can be summed up into two types of support areas, shown in Figure 11 which illustrates a system to protect the airway and Figure 12 which shows a full coverage support system. Also, an instrumented site of each support system was conducted mid-pillar.
To instrument these test sites in (Mirabile) case study the Jackpacks were installed between the top of the interlocking wooden cribs and the mine roof, while the Jackpacks for the pumpable crib were installed between pumpable crib and mine floor. Water resistant plywood was installed above and below the Jackpacks to help with the stabilization and to provide a flat contact surface. Inflatable metal bladders (Jackpacks) and string potentiometers were used to collect loading and convergence data, respectively (Mirabile, B., and Westman, E., 2019). The string potentiometers were installed at the top of the crib supports and anchored to the bottom of the crib supports.

Due to possible leakage of the Jackpacks in first testing area unreliable data was collected, ruling out the maximum load established on the crib supports. Leakage has been observed in these Jackpacks previously in other studies conducted on crib support loading characteristics. With the string potentiometers in place that data can provide displacement of the cribs as the longwall face advances. A comparison can be prepared between the displacement data collected and data contained within the NIOSH STOP database to produce a load curve.

Data analysis of both the loading and displacement of the standing supports was collected for the remainder of the test site. When the conditions deteriorated the data
logger for the instrumentation was removed so the data would not be lost in areas no longer accessible. Load cell data from the two support strategies supported with pumpable supports suggest that the allowance of partial entry failure may induce abutment load transfer to mine pillars as predicted by GRC concept (Mirabile, B., and Westman, E., 2019).

From the in-situ results of support loading characteristics measurements and convergence instrumentation a ground response curve can be generated. A standing support must maintain its integrity during the uncontrollable convergence that occurs, while providing support to the immediate mine roof while further convergence emerges. When a standing support is too stiff compared to the ground response curve for that given area the support will yield its load once peak load is achieved. Load sheading allows the standing support to reach peak load before it begins to shed its load by deforming. A specific standing support system that is installed can impact the behavior of the ground response curve.

The loading and convergence data analysis collected at the NIOSH STOP program illustrates in a controlled laboratory environment the results of each type of standing support available. When specific data is lost due to instrumentation failure an assessment of that support behavior can be determine by referring to the data acquired in the NIOSH STOP program.
Chapter 3: An Improved Load Measuring Device for Underground Mining Standing Supports

3.1 Abstract

Standing support is often used in conjunction with underground retreat mining. Knowledge of the load-displacement behavior of a standing support, and loading induced by the mine opening is critical to proper support selection. The NIOSH STOP database contains load-displacement laboratory test data for most commonly used standing supports. Hydraulic load cells currently used to measure in-situ loading of standing supports have exhibited leakage under load, producing irregularities within the dataset. An improved hydraulic load cell eliminates leakage and produces more consistent data.

3.2 Introduction

A hydraulic load cell, more commonly known as flat jack or JackPack, is a device installed to determine the loading characteristics of roof to floor supports. These standing or roof to floor supports include, but are not limited to: pumpable cribs, cans, wooden cribs (4-point, 9-point, etc.), metal props, wood timbers, concrete donut cribs, and other variations of these standing supports.

Flat jack devices have been used previously to determine the loading of such roof to floor supports. The most commonly used load cell for standing supports is based on a design intended for pre-stressing standing supports, not load measurement. Preloading helps to keep the supports, such as timbers props and cribs, in place during the dynamic loading associated with blasting (Barczak, T.M., and Tadolini, S., 2004).
Flat Jacks are manufactured in various shapes and sizes depending on the application, common shapes are square and round that are 25.4 mm (1.0 inch) thick when collapsed as shown in Figure 13. These load cells are produced in South Africa, and can be formed into several different shapes depending on the applications (Barczak, T.M., 2003). The sheet metal that makes up the bladder is comprised of 19-gauge or 1.11125 mm (0.04375 inch) thickness; the top and bottom pieces of sheet metal are resistance seam welded around the perimeter. There are two different ports installed on one of the bladder skin corners of the flat jacks; these ports allow a fluid to fill the unit and the other port has a relief valve. The fill port is comprised of a check valve. The pressure relief valve is located in the second port; preset to 1,724 kPa (250 psi), pressure relief valve will keep the load cell from bursting. Bursting of these load cells typically causes a small tear in the metal skin allowing the fluid to leak out without a large catastrophic failure.

The effective inflation range of these load cells is between 25.4 mm (1.0 inch) to 254.0 mm (10.0 inches) thick. Different types of fluids can inflate these load cells but the most common and easily accessible fluid for testing applications is water. Water pressure from the mine supply line can inflate these load cells to the desired load. Depending on the pre-stressing requirements a pneumatic powered pump, hydraulic pump or hand pump may be required to inflate the load cells.
3.3 Statement of Problem

Testing has been conducted previously on the current flat jack that is available for purchase. A common issue recognized in a majority of cases concerning these flat jacks is leakage. As field-testing was performed, the instrumentation on pumpable cribs were not functioning properly, possibly due to leakage (Klemetti, T.M., Van Dyke, M.A., and Ihsan, T.B., 2017).

Leakage has occurred in several instances where the fill valve has malfunctioned or the resistance weld along the perimeter has failed. The fill valve port is the main source of the leakage. The fill valve is a check valve comprised of a ball and spring inside the fill port. Visual observations conducted along with field-testing indicate that fifty percent of the flat jack fill ports were compromised.

3.4 Improved Load Measuring Device

Consistent performance of a load is critical to a reliable data collection program. This is true whether data is collected in the field or laboratory setting. When leakage occurs during any type of testing, the result is an unreliable data set or will skew the testing outcomes. To help improve in the reliability of measurements taken from pre-stressing or monitoring roof to floor support-loading characteristics, a redesign of the flat jack was initiated.

The basic principles of operation of the current flat jack were not changed; improvements were developed in the fill ports and welded seams. Prototypes of the updated design of the Fluid Filled Load Monitoring Device (FLMD) were produced for testing. On these prototypes, both of the ports were welded to the outer bladder flange. Figure 14 displays the outer flange, a new addition to these hydraulic load cells. On prior designs, the ports were located on the top portion of the bladder skin. These new ports are comprised of a standard 6.35 mm (0.25 inch) FNPT (American National Pipe Thread). With a standard size port, the inlet port can be adapted more easily to the type of connector readily available at the mine site or in laboratory testing. Current hydraulic load cells require a specialized fill nozzle that is only available from the manufacturer of
these hydraulic load cells. The second port also is comprised of the same standard port 6.35mm (0.25 inch) FNPT to allow installation of different instrumentation devices and/or relief valve connected seamlessly.

![Prototype FLMDs with flange and side ports.](image)

The new position of these ports to the side allows superior access to fill the bladders and any installed instrumentation. This new location also reduces the chances of roof to floor support interfering with the ports location when attached to the side flange of the load-measuring device.

Improvement of the welded seam around the perimeter of the bladder of the FLMD is also critical in eliminating cell leakage. The current hydraulic load cell is resistance seam welded. The welding procedure on the first prototype, FLMD-1.0, was a butt weld between the 50.8 mm (2.0 inch) side flange and the bladder skins. The bladder skins for the top and bottom remain constant of 19-gauge or 1.11125 mm (0.04375 inch) thickness. The single square–groove weld was welded using the Gas Metal Arc process (GMAW) utilizing 0.762 mm (0.030 inch) wire. Two additional weld joints were reviewed: chamfer and v-groove welding utilizing the GMAW process and 11.94 mm (.047 inch) wire.

Welding was conducted by qualified welders to the American Welding Society Standards (AWS) D1.1 structure steeling welding code. The GMAW process was used with a shielding gas mixture of 85% Argon/15% CO2. The filler metal used conformed to AWS D1.1 specification A4.18, Classification ER70S-6 as listed in Clause 4, Table 4.9.

### 3.5 Inspection of FLMDs

Inspection of the new FLMDs manufactured went through a nondestructive testing (NDT) before they were introduced to the load-testing machine. This testing procedure is vital in the location of weld defects and determining the nature of the defects (Inspectioneering, 2018). The nondestructive testing was performed per the guidelines of the American National Standard Institute (ANSI) and the American Society for Nondestructive Testing (ASNT).

The NDT is a way to determine any manufacturing defects along the welded seams of the FLMDs after the manufacturing process. This inspection would determine if the FLMDs are safe for testing. First a visual inspection or visual testing (VT) was conducted on the weld seams, this was accomplished with the naked eye to determine if any external areas of the welded perimeter shown signs of possible future failures. Conducting the VT of the welded seam can detect surface flaws that include weld undercut, cracks, porosity and unfilled craters.

Another testing method was utilized after manufacturing the new FLMDs was a leak test (LT). Leak testing will detect if a hole or porosity in the weld is capable of passing fluid from the high pressure inside the FLMD to the lower pressure outside the FLMD. Two types of LTs were performed a bubble leak test and pressure change method. For the bubble testing procedure we introduced air into the each of the FLMDs to achieve a pressure rating of 206 kpa (30 psi). Then the FLMDs was lowered into a water bath to observe any air bubbles escaping through the welded seams. NDT testing was conducted in accordance with ASTM E515-11 (American Society for Testing and Materials, 2018).

A third nondestructive testing procedure, the pressure change method, was conducted on the FLMDs as part of the LT process. During this testing procedure, the FLMDs were filled with compressed air to 206 kpa (30 psi). Pressure was monitored for 30 minutes to determine if pressure change in each of the FLMDs tested.
During the inspection stages of the FLMDs, if any weld failed the VT or LT testing, then each area was marked and sent back to manufacturing for corrective action and NDT was conducted once again.

### 3.6 Laboratory Testing

Laboratory testing was conducted at Jennmar Corporation Specialty Products facility. A 1993 kN (200 t) capacity calibrated hydraulic load-testing machine was used for testing all load cells. Water was used to fill these hydraulic load-measuring devices. The current hydraulic load cell “flatjacks” could be filled with a standard municipal water tap. Depending on the water pressure from the municipal source, a booster pump (pneumatic-powered pump, hydraulic PTO pump, or hand pump) may be required (Heintzmann, 2018).

A pressure transducer was installed on the second port of the hydraulic load cells. For the flatjacks, the pressure transducer was installed after the pressure relief valve was removed. The removal of the pressure relief valve was necessary to instrument the hydraulic load cell, as the load cell only has two ports. The FLMD versions of the hydraulic load cells had two ports as well installed on the side of the load cells. As with previous hydraulic load cell one port is used to fill the bladder with municipal water and the other port was to allow instrumentation of a pressure transducer.

#### 3.6.1 Testing Current Hydraulic Load Cells

Testing was conducted on numerous flatjacks currently in production. As previously stated, a common issue with current flatjacks was leakage at the fill port check valve. Throughout testing several flatjack ports allowed water to pass the check valve to fill the bladder, but once load was introduced, the ball above the spring did not seal the area well, causing leakage.

Another failure mode occurred during filling. When the check valve was depressed with the fill nozzle, the spring and ball of the check valve becomes jammed in the open position. Allowing filling fluid to run freely back out of the bladder before any
load could be introduced. Fill port valves on other flat jacks were stationary in the closed position, allowing no fluid to pass through the check valve to fill the bladder. The area inside the check valve was corroded with rust. To help keep debris out of the fill port it was outfitted with a plastic sleeve to keep foreign material from entering the port.

3.6.2 Improved Hydraulic Load Cell Testing

3.6.2.1 FLMD-1 Prototype

The first generation of the FLMD-1.0 in Figure 15 was constructed with a 50.8 mm (2.0 inch) flange on edge of the bladder. A butt weld was made between the bladder skins. Two ports were welded to the side flange. Municipal water was introduced to the first fill port until the bladder was full and the water was running out of the second port. Once the bladder was full of water the second port was closed off with a pressure transducer. Then additional water was applied to the bladder to cause slight expansion. As water was applied at second time to the bladder of FLMD-1.0, a leak occurred due to the weld variance. The leak was observed on all FLMD-1.0 prototypes shown in Figure 16.

![Figure 15: FLMD-1.0 prototype compared to flatjack.](image)
3.6.2.2 FLMD-2.0 Prototypes

The next prototype hydraulic load cell FLMD-2.0 was developed with a flange ring around the perimeter of the cell thicker than the bladder skin as Figure 17 illustrates. This allowed a corner joint weld to be performed on the first skin on the inside and outside of the bladder. Then second skin was recessed down to allow for an outside corner joint weld. The corner joint weld with the single square-groove specifications B-L1a_GF without backing as noted in AWS D1.1 Clause 3; Figure 3.5 performed best of the various weld joints tested (American Welding Society, 2015).
Using similar filling procedures as FLMD-1.0, FLMD-2.0 was filled with municipal water until the bladder was full. After initial filling, a pressure transducer was installed in the second port. The FLMD-2.0 was pressurized with water until the bladder’s skin expanded from the initial 50.8 mm (2.0 inch) thick to 101.5 mm (4.0 inch). The pressure transducer was wired to a Miniature Data Acquisition System (MIDAS) to capture pressure data within the FLMDs shown in Figure 18.
The Miniature Data Acquisition System (MIDAS) consists of multiple equipment components working together to provide a high precision analog-to-digital data-logging system capable of wired or wireless operation (NIOSH National Institute for Occupational Safety and Health, 2012). The system also can be used underground where a need for intrinsically safe environment approved by Mine Safety and Health Administration (MSHA).

Once a load was applied to this fluid filled load-measuring device, the load increased uniformly. Early termination of testing this load cell was due to the uneven load distribution from the hydraulic load-testing machine as observed in Figure 19. Two of the load cells on the load-testing machine show lower loads applied and minimum movement compared to the other load cells on the testing machine. At this termination point the FLMD-2.0 reached a capacity of 191.3 kN (19.2 t) with the inside pressure revealed 182.5 kpa (26.5 psi) shown in Figure 20 and Figure 21 respectively.

Additional FLMD-2.1 and FLMD-2.2 testing was conducted. Initial setup of these was two units identical to previous testing. The FLMD-2.1 achieved a capacity of 542.0 kN (54.4 t) with the inside pressure revealed 466.8 kpa (67.8 psi) shown in Figure 20 and Figure 21 respectively. This test was terminated prematurely due to leakage at the top weld seam. The leak was minimal, a very small pinhole within the welded side flange.

The next FLMD-2.2 test showed promise in achieving 1494.6 kN (150 t) to 1992.8 kN (200 t) goals. As this test reached its maximum capacity of 996.4 kN (100.1 t) the internal pressure was 861.5 kpa (125.0 psi) with no leaking. The results are shown in Figure 19 and Figure 20 respectively additional testing results are located in Appendix B. This test was terminated early due to deflection of the frame fixture holding the FLMDs. Deflection in the fixture will create inconsistencies in the dataset.
3.6.2.3 **FLMD-3.0 Prototype**

The third prototype hydraulic load cell FLMD-3.0 was developed with the side flange even with the bladder’s skin. A v-groove weld was used on the seam between the side flange and the bladder’s skin. Detail drawings of the FLMDs tested are illustrated in Appendix A. Again two ports were welded to the outer side flange for filling the load cell and installation of instrumentation on the other port.

As with the other FLMDs the FLMD-3.0 load cell was filled with municipal water with the pressure transducer attached, then pressurized to expand the skins of the bladder to 101.5mm (4.0 inch). The load was uniformly increased from the hydraulic load-testing
machine. At 149.5 kN (15.0 t) a small leak occurred at the v-groove welded seam. As shown in Figure 22, the testing continued until 186.3 kN (18.7 t) were reached, with leakage continuing. Again uneven load distribution illustrated in Figure 22 was observed on the hydraulic load-testing machine. The pressure inside the FLMD-3.0 at time of termination reached 216.1 kpa (31.3 psi) shown in Figure 3.9.

![Figure 22: Individual load points for FLMD-3.0.](image)

### 3.7 Frame Fixture Design

During testing of the FLMD-2.0 and FLMD-3.0 prototypes the hydraulic loading-testing machine revealed uneven load distribution shown in Figure 19 and Figure 22. The metal frame fixture that held the FLMDs in place during testing began to deflect as load was applied. A robust frame fixture design is necessary to maintain an even load distribution during testing of FLMDs.

#### 3.7.1 Current Frame Fixture Design

The current frame fixture is positioned inside the load-testing machine to remove the additional space, thus allowing minimum movement of the hydraulic rams to extend as they are applying load on the FLMDs. The current frame fixture design is comprised
of nine W4x13 beams welded together to form a top and bottom frame plate. Between the two frame plates a 996 kN (100 t) steel prop is placed at each corner with a 548 kN (55 t) steel prop in the center illustrated in Figure 23. The placement of the FLMDs during testing is centered above the top frame plate allowing the middle platform of the hydraulic load-testing machine to load in the vertical downward direction.

As pressure develops during testing, uneven load distribution is encountered. When additional load is applied, measured load values from individual load cells begin to yield greater variance. After inspection of the data of each load cell along with visual observation of the frame fixture, the determination was concluded that the frame is the main source of inaccurate data. Deflection of the top and bottom frame plates was visible as the load increases; the maximum yielding location occurred as the center metal prop began to puncture the top and bottom frame plates.
3.7.2 Updated Frame Fixture Design

A ridged frame fixture is necessary in order to produce consistent controlled laboratory test data that can be applied to calibrate field-testing data. The next generation of the frame fixture introduced will involve a complete redesign. The bottom plate and top plate mirror each other comprising of nine W4x13 beams, gussets centered on 152.4 mm (6.0 inch) and then a 12.7 mm (0.5 inch) flat plate on the top and bottom of each beam platform. Three steel square sets were placed between the top and bottom beam platform assemblies manufactured with W4x13 beams and cross members as shown in Figure 24.

![Figure 24: Frame assembly with top and bottom plates.](image)

To evaluate frame rigidity and safety factor, Analysis System (ANSYS) structural analysis software was applied. The finite element analysis (FEA) was conducted using the following parameters; 609.6 mm (24 inch) diameter loading area with a maximum of 2491 kN (250 t). The loading area is positioned center of the top beam platform. As the vertical load is applied to the square set frame fixture, the I-beam legs, center of the top
plate and the four corners of the top and bottom platforms began to display high concentration loading, resulting in a safety factor less than 1.0 as shown in Figure 25. When the safety factor is lower than 1.0 indicates that the material yield or failure can occur in these areas of the model. Applying the FEA software to the redesign before manufacturing begins allows for necessary adjustments of the frame design. These modifications to the frame design permit trial and error approach until the safety factor is above 1.0 and no failure will occur when testing the FLMD’s with the load-testing machine.

![Figure 25: Safety factor of rigid frame](image)

An updated design for the frame fixture will be required to allow for the increase of the safety factor of 0.53 to above 1.0. The goal is to reduce deformation and/or material failure due to the vertical loading of the hydraulic load-testing machine. Shown in Figure 26 an additional I-beam was installed in the center of the middle square set along with base gusset plates on each corner of the top and bottom frame platforms, and a cap plate attached to the top and bottom of the frame platforms created from the I-beams placed in the horizontal direction. Additional design features for the frame fixture is illustrated in Appendix C.
Once the vertical load is applied to the updated rigid reinforced frame fixture the maximum amount of deflection on the top plate platform is now 2.007 mm (0.079 inch) and the minimum safety factor of 1.0 has now been achieved, this can be observed in Figure 27.

Figure 26: Reinforced frame structure.

Figure 27: Safety factor of reinforced frame
Now when the FLMD or flat jack is installed in the hydraulic load-testing machine and placed above the new rigid reinforced frame the information from the FEA analysis will determine the calibration factor of the flat jacks. When deformation occurs once a maximum vertical load is applied in the hydraulic load-testing machine a total of 2.007 mm (0.079 inch) has occurred just within the frame structure. The next step will be to find out the maximum deformation occurs to the hydraulic load-testing machine frame structure while this vertical load is introduced.

### 3.8 Hydraulic Load-Testing Machine

During the investigation of the hydraulic load-testing machine once a standard size cementitious pumpable crib and or any standing support system was installed in conjunction with the fluid filled load-measuring device vertical clearance became an issue. Then with the possible introduction of new technologies in standings supports systems, additional vertical movement of the platform is desirable for the opportunity of extreme extents of deformation. The current hydraulic load-testing machine located in Cedar Bluff, Virginia has a vertical movement limited to 304.8 mm (12.0 inch). Vertical movement of the MRS located at NIOSH testing facility is limited to 609.6 mm (24.0 inch) without readjusting the machine. Resetting the machine to a lower level and developing different testing frame extensions required to further apply a load to the standing support in the load-testing machine can be very cumbersome, timely and could lose valuable data. To help assist in further development of high displacement standing supports the hydraulic load-testing machine must be modified to accommodate the extended hydraulic cylinder travel requirement.

To analyze the stability of the current hydraulic load-testing machine shown in Figure 28, the testing frame which is subject to a maximum vertical pushing loads of 2989 kN (300 t) was applied onto the standings supports installed in the load-testing machine. The hydraulic load-testing machine frame structure consists of the following parts; top platform, four hydraulic cylinders, middle platform and base plate as illustrated
in Figure 29. At the top platform four hydraulic cylinders are attached between the top and middle platforms. The middle platform will push in the downward vertical direction against the top of the standing support installed within the hydraulic load-testing machine which currently has a maximum extension of 304.8 mm (12.0 inch).

![Figure 28: Current hydraulic load-testing machine.](image)

![Figure 29: Components of hydraulic load-testing machine.](image)

### 3.8.1 Numerical Structural Analysis of Hydraulic Load-Testing Machine

With the current hydraulic load-testing machine the frame was loaded with 2192 kN (222 t) without any excessive deflections or yielding. Therefore, calibration of the simulation results with a 2192 kN (222 t) of load is first implemented and the simulation results with a 2989 kN (300 t) of load are then compared.

A 1369 kPa (28.6 ksf) was applied as a uniform load to the top plate platform. This represents the maximum load that can be applied from the new long extension hydraulic cylinders attached to the top plate and the standing supports inside the frame of the machine. The new hydraulic cylinders parameters allow for a 2989 kN (300 t) maximum combined vertical load and total stroke length to 914.4 mm (36 inch)
compared to the current design stroke length of 304.8 mm (12 inch). The load and boundary conditions are shown in Figure 30 for the numerical structural analysis.

\[ F = m \times a \]

\[ 600 \text{kips} = m \times (4\text{ft} \times 5.25\text{ft}) \]

\[ m = 28.6 \text{kips/ft}^2 \]

Figure 30: Loading and boundary conditions.

The American Institute of Steel Construction (AISC) steel codes are listed in Table 2 per the Load and Resistance Factor Design (LRFD) method. Per this table the W8 x 40 I-beam construction of the load-testing frame is 0.57 which is less than 1.0, making the main vertical beams stable under the 2989 kN (300 t) load subjected from the four hydraulic cylinders. The frame structure horizontal members consist of W6 x 25 I-beams and C10 x 15.3 C-channel, the c-channel members are positioned between the vertical legs for added support stiffness illustrated in Figure 30. Specification of W8 x 40, W6 x 25 I-beams and C10 x 15.3 C-channel listed under Appendix D.
3.8.2 FEA model simulation of hydraulic load-testing frame

Testing conducted previously on the hydraulic load-testing machine indicates that a maximum load of 2192 kN (222 t) was applied on the hydraulic jack brackets and platforms with minimum deflections or yielding generated on the I-beam members. A Finite Element Analysis (FEA) model was initiated to establish testing forces applied at 2192 kN (222 t) and 2989 kN (300 t) respectively to determine any deformation, stress concentration and safety factor concerns on the hydraulic load-testing machine frame. The standing support incorporated into the model is a cementitious pumpable crib, the mechanical properties of the pumpable crib and components of the testing frame are listed in Table 3.

<table>
<thead>
<tr>
<th>Item</th>
<th>Young's Modulus (lb/in²)</th>
<th>Poisson’s ratio</th>
<th>Density (lb/in³)</th>
<th>Minimum yield stress (lb/in²)</th>
<th>Minimum tensile strength (lb/in²)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel plate, angle bracket, gussets</td>
<td>29,000,000</td>
<td>0.3</td>
<td>0.283</td>
<td>36,259</td>
<td>66,717</td>
<td>ASTM A36</td>
</tr>
<tr>
<td>I-Beam</td>
<td>29,000,000</td>
<td>0.3</td>
<td>0.283</td>
<td>50,000</td>
<td>65,000</td>
<td>ASTM A525</td>
</tr>
<tr>
<td>J-Crib</td>
<td>300,000</td>
<td>0.45</td>
<td>0.035</td>
<td>450</td>
<td>600</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Mechanical properties of frame components.

* Properties of J-Crib for modeling purposes

Once the load of 2192 kN (222 t) and 2989 kN (300 t) respectively is applied in the FEA model on the hydraulic load-testing machine frame, Figure 31 and Figure 32.
shows the maximum deformation occurs on the middle platform. Additional views of the
deformation on the top platform and middle platform can be observed in Appendix D. At
2192 kN (222 t) loading force the maximum deformation was created throughout the area
around the steel flanges attachment points for the hydraulic cylinders resulting in 5.84
mm (0.23 inch) total deflection. When the load was increased to 2989 kN (300 t) the
maximum deformation occurred at same location but increased to 7.87 mm (0.31 inch)
ultimate deflection.

![Figure 31](image1.png)  
**Figure 31:** Deformation of hydraulic load-testing machine frame at 220 tons.

![Figure 32](image2.png)  
**Figure 32:** Deformation of hydraulic load-testing machine frame at 300 tons.

Safety factor is calculated based on the maximum shear stress theory and is
defined as the ration of half the yield strength of materials to the maximum stress
calculated in the FEA model. Safety factors 1.0 – 3.0 are acceptable design criteria, a
safety factor below a 1.0 indicates that the material yield or failure can occur in these
areas of the model. The safety factor for the 2192 kN (220 t) load applied yielded a result
greater than 1.0. Once 2989 kN (300 t) load was applied the middle and top platforms
exhibit areas less than a 1.0 safety factor, illustrated in Figure 33. Additional views of the
safety factor FEA model can be observed in Appendix D.
3.8.3 Hydraulic load-testing frame modification

During the FEA simulation high stress zones and safety factor below 1.0 are on the original top frame platform and middle frame platform. Reinforcements in these areas are critical for the hydraulic load-testing machine frame to achieve 2989 kN (300 t) applied load capacity without permanent steel member distortion.

To strengthen the top frame platform and middle frame platform assemblies an additional four W6 x 25 I-beams was installed between the I-beams originally mounted in each platform. Once the FEA model was loaded at the maximum allowable load applied by the hydraulic cylinders of 2989 kN (300 t) it revealed a smaller deformation. The deformation was reduced down to 5.59 mm (0.22 inch) with the 4 additional I-beams installed in the middle and top frame platforms as shown in Figure 34, the original design yielded a result of 7.87 mm (0.31 inch) deflection. With the new proposed design a total deformation reduction rate of 28.9% was achieved. Deformation of the added support I-
beam supports for the hydraulic load-testing machine frame platform assemblies are illustrated in Appendix D. With the reduction of the maximum allowable deflection is similar to the calibration testing conducted at 2192 kN (220 t) which yielded a maximum allowable deformation of 5.84 mm (0.23 inch).

![Figure 34: Deformation of reinforced hydraulic load-testing machine frame.](image)

The safety factor of the reinforced hydraulic load-testing machine frame has also been reduced with the addition of W6 x 25 I-beams installed on middle and top frame platforms. Very few areas still show less than 1.0 safety factor, these areas pose the potential for localized steel yielding and will not compromised the stability integrity of the frame when 2989 kN (300 t) of pushing force is applied to the standing support and machine frame. As seen the Figure 35 the inspection of the color-codes as follows (red, SF < 1; yellow, 1 < SF < 3; orange, 3 < SF < 5; green, 5 < SF < 10; blue, 10 < SF < 15).
With both structures reinforced for up to a maximum allowable load of 2989 kN (300 t) of the hydraulic load-testing machine frame structure and the frame fixture, a determination of total deflection can be associated to the fluid filled load-measuring devices. These maximum allowable deformations are 5.59 mm (0.22 inch) and 2.01 mm (0.08 inch) respectively, totaling 7.60 mm (0.30 inch) for both hydraulic load-testing machine frame structure and the frame fixture. Measurements of deformation for these two components within the workings of the testing machine are considered a critical component of information for further calibration models generated by various standing supports and/or load-measuring devices to be load tested in the hydraulic load-testing machine.

**3.8.4 Testing and redesign review**

The concept of introducing a new load-measuring device has initiated several versions to be manufactured for testing to determine the correct welding process. The
goal is to eliminate the potential of pre-mature failure along the weld seams. The current JackPacks manufactured are resistant seam welded. Three types of weld joint were utilized in testing the new generation FLMDs, butt weld, v-groove weld and corner joint weld. Of the three weld joints, the corner joint weld showed the most promise by reaching a maximum capacity of 996.4 kN (100.1 t) with an internal pressure of 861.5 kpa (125.0 psi) with no leakage observed.

By eliminating the check valve on the current manufactured JackPacks has removed the potential for any corrosion to occur in the fill port. Transitioning from a specialized fill nozzle to the 6.35mm (0.25 inch) FNPT threaded port has provided superior versatility at the mine site allowing instrumentation for laboratory and in-situ testing more easily. Evaluation of the current JackPacks produced in South Africa demonstrated a failure rate of fifty percent at the check valve location.

When high loading of the frame fixture was induced by the load-testing machine extreme deformation of the frame fixture posed inconsistencies in load curve created by the load cells attached to the hydraulic load-testing machine. With the tremendous deflection observed on the frame fixture, a redesign was required to alleviate the possible failure when 2989 kN (300 t) load is reached. Early termination of the testing of FLMDs occurred with extreme deflection was observed in the frame fixture when the load reached 996.4 kN (100.1 t) on the corner-joint weld FLMD. During the redesign of the frame fixture several versions were created to maintain a safety factor above 1.0 in the ANSYS FEA program.

Another project that was introduced into the initial design of load-measuring device on underground standing supports was the increase of the capacity of the hydraulic load-testing machine to 2989 kN (300 t) and to increase the middle platform vertical movement from 304.8 mm (12 inch) to 914.4 mm (36 inch). Calibration of the current design of the hydraulic load-testing machine was perform at 2192 kN (220 t) to gain a base line deflection. With the redesign at 2989 kN (300 t) load was applied to various versions to achieve a safety factor above 1.0. Each version of the hydraulic load-testing machine designs increased in stiffness by adding additional steel members in the top and middle platforms.
With the redesign of the frame fixture and hydraulic load-testing machine completed with acceptable results conducted within the FEA program, the next step is to return to the design of the FLMDs. As the hydraulic load-testing machine increased the vertical load being applied to the FLMDs it produced folding of the metal skins and fractures in the weld joints in all other prototypes. The corner joint weld was the only prototype that was able to achieve higher level of loading compared to the other two prototype weld joints tested. As the fractures appeared within the weld joints water began to spray out of these areas and at this moment testing was terminated. Robust weld joint to achieve the 1993 kN (200 t) with the addition of the side flange will be challenging. Additional research and discussions with other welding manufacturers of high-pressure vessels would be beneficial in creating the next generation load-measuring device for underground standing supports.
Chapter 4: Summary of Results and Conclusions

An improved hydraulic load cell is currently in development to collect more reliable and consistent load measurements on standing supports. Whether testing is conducted in the laboratory or in the field, a reliable load-measuring device can provide valuable data on the behavior of standing supports. Leakage of load cells has produced unreliable data or data that cannot be used to evaluate the loading effects on the standing supports. Initial development and testing of four load-measuring devices has addressed issues of leakage through the fill ports up to a load of 1007.4 kN (100.1 t). Removal of the check valve has eliminated this failure point. The check valve located in the fill port of the existing flatjack failed at a rate of 50% due to corrosion inside the valve. This corrosion is the main source of failure detected in testing conducted in the laboratory setting. Previously research conducted for in-situ data collection using the current JackPacks illustrated corrosion issues also when calibrating each of the load-measuring devices. Before each of the load-measuring devices are installed on roof to floor standing support a calibration is needed to determine if a failure will occur before peak load is reached and to determine a load displacement versus inside pressure dataset curve.

Similar load-measuring devices that are utilized in different industries and have diverse installation procedures are hydraulic load cells. These load cells are comprised of stainless steel or aluminum housing depending on the pressure that is to be induced by an array of loading conditions. The shape of these hydraulic load-cells are typically low profile, reduced vertical displacement and lesser in diameter than the hydraulic load-measuring devices discussed for underground standing supports. These hydraulic load-cell units are typically filled with hydraulic oil with ports protruding from the load cell to connect instrumentation. Typically, these units are applied in a laboratory settings and used on bridge scales. To help alleviate the possibility of corrosion disruption on the hydraulic load-measuring devices presently installed in underground mines on standing supports a major benefit can be concluded that using stainless steel and hydraulic oil would diminish the corrosion issues with metal components and water.

Proper seam welding has been found to be a crucial part of the redesign and manufacture of these hydraulic load-measuring devices. The resistant seam welding is
currently being used on Jack Packs from South Africa; this welding procedure is ideal for welding two thin 19 gauge pieces of sheet metal together along the perimeter to construct an inflatable bladder. As the load is applied, it creates flex in the skins of the bladder and the side flange, this movement allows the weld to flex as well. When the weld joint is flexed to its maximum point, pinhole leaks occur along the seam. The corner joint seam weld was best at maintaining its integrity as the bladder skins flexed and the pressure inside the FLMDs increased. Once the welding of the seams was completed, non-destructive testing was conducted on each of the load-measuring devices. Each load-measuring device was tested using the visual and bubble test to determine the integrity of the different weld joints. Due to the welding procedures, several of the FLMDs had to be reworked in specific areas, the weld joint allowed pressure differential to occur.

With the request of the introduction of a side flange creates the opportunity to review different welding procedures to attach the thin metal skins to the side flange. The addition of the side flange allows the transfer of the ports from the top skin location to the side flange location. Relocating the ports to the side flange will reduce the potential damage of the instrumentation attached to the hydraulic load-measuring device; potential hazards include floor heave, standing support deformation and immediate roof failure. Reducing the risk of damaging the instrumentation in the underground environment is at times challenging but is vital on gaining reliable data.

As testing of the completed preliminary hydraulic load-measuring devices was conducted in the load-testing machine the frame fixture poses issues when it reached its peak support capacity of 996.4 kN (100.1 t). The frame fixture was constructed of steel props and top and bottom platforms. The peak load of the steel rigid props was reached and began to puncture the platforms attached. The new redesign of a frame fixture to fit inside the hydraulic load-testing machine was introduced to eliminate the potential for the frame fixture failure and extreme deformation. Two design concepts of the frame fixture were created, and then a finite element analysis was performed to conclude the most robust design for the load capacity that will be introduced. By adding additional W4-13 steel members and gussets permitted increased stiffness. The FEA program allows creation of various loading conditions to generate a load distribution curve.
As with many projects, a person/teams who work diligently on projects will produce a potential for additional projects to be completed within the scope of the first task. When working to create a new design or alter a current design to generate a more robust item or system could reveal weakness in other components in that system. This research conducted for an improved load-measuring device for underground mining standing supports began as a project to include two changes to current design of the load-measuring device. When manufacturing these new concepts included researching and reviewing with various manufacturing plants on welding procedures it was determine to try these three welding techniques discussed. The introduction of new welding technique along with the side flange installed has been challenging to manufacture with a weld joint capable of the inflation pressures that at 1993 kN (200 t) produces. With the major deformation and the frame fixture during testing of the load-measuring devices another project was introduced to create a more rigid frame fixture. Changes to the frame fixture took several revisions to gain sufficient strength and reduced deflection to an acceptable point. Following mini project within the main project an announcement of updating the hydraulic load-testing machine to accomplish a higher rating capacity and longer stroke lengths for the potential of high yield standing supports. By creating, a longer stroke length from 304.8 mm (12 inch) to 914.4 mm (36 inch) would introduce an industry leading hydraulic load-testing machine for standing support.

With the potential introduction of a new hydraulic load-measuring device for standings supports would have promise for future research in the following mining operations; coal, salt and other hard rock mines that creep or deformation of the rock strata occurs. Depending on the mineral being extracted and geological conditions encounter the potential to use hydraulic load-measuring devices on standing supports could be universal by obtaining valuable data for engineers to enhance the understanding of ground response curve in that given area. With the potential of corrosion failure due to the metal being exposed to acidic conditions in the underground environment, the opportunity to review stainless steel bladders could be a great attribute to the future design and testing of the load-measuring devices.
4.1 Future Work

Since the design of the hydraulic load-testing machine and frame fixture has been completed and validated, the next step would be to begin detail-manufacturing drawings of each component and to create a bill of materials. After the drawings to be completed, manufacturing of the components would be initiated. Assembly and modifications of the hydraulic load-testing machine would take place while to try to increase the machine capacity to achieve a higher load rating along with an extended stroke length to 914.4 mm (36 inch) with the new hydraulic cylinders.

Further research and testing will be conducted to provide a successful example of the load-measuring device. These fluid filled load cells will see a maximum load of 1993 kN (200 t) and be able to maintain pressure basically indefinitely.

The end goal of this research project is to create a hydraulic load-measuring device that will monitor varying loads and displacements on standing supports. These devices will need to be calibrated and will need to maintain their integrity for the duration of the research at the mine site location. The data that is captured from data-loggers attached to the load-measuring devices can help inform engineers of ground reactions curves created from this new information gathered from the hydraulic load-measuring devices to make more educated decision and design a safer work environment in the future.
References


Appendix A:

Appendix A shows the examples of the current Jackpacks versus the new FLMDs tested in the hydraulic load-testing machine. A segmentation of the check valve in the inflation port is shown in Figure B. Detail drawings of the FLMDs designs is shown Figures E, F and G. Figures H, I, J and K all illustrate an inflation port installed along with a pressure transducer. The pressure release valve was removed; this port was later used for inflation and instrument measurements.

(a) Various Shapes of Current FlatJacks

(b) Check Valve Internal Mechanism

(c) Specialized Fill Valve Adaptor
(d) Pressure Relief Valve Instrumented with MIDAS

(e) Detail view of FLMD-1.0

(f) Detail view of FLMD-2.0, 2.1, 2.2

(g) Detail view of FLMD-3.0
(h) Fill Port with FLMD Inflated with water

(i) Initial Testing Frame within the Load-Testing Machine

(j) FLMD 2.0 Weld Failure

(k) FLMD 2.1 762 mm (30 inch) Diameter with Pressure Transducer
Appendix B:

Appendix B illustrates the loading graphs of the various FLMDs tested. Noticeable in Figures (a) and (c) that the hydraulic load-testing machine was not performing with equal load distributions across all load cells during testing.
Appendix C:

Appendix C includes basic dimensions and design details of the new reinforced frame fixture. As Figure B illustrates, the increased reinforcement of metal plate gussets across the bottom of the frame fixture ensures a reduced deformation of the bottom of the platform. Figure C show, the FEA deformation analysis of 250 ton force acting on the frame fixture.

(a) Reinforced frame detailed

(b) Reinforced frame bottom platform

(c) Reinforced frame deformation 250 tons
Appendix D:

Appendix D includes dimensions in inches of the W8 x 40, W6 x 25 and C10 x 15.3 beams and c-channel used to design the hydraulic load-testing frame structure. Also the figures illustrate the FEA analysis of total deformation along with the safety factors and total deformation of an array of different reinforcements attributed at 2192 kN (220 ton) and 2989 kN (300 ton) capacity.
(e) Load-testing frame at 300 tons

(f) Load-testing frame bottom view at 220 tons

(g) Load-testing frame bottom view at 300 tons

(h) Safety factor top platform 220 tons

(i) Safety factor top platform 300 tons

(j) Safety factor middle platform 220 tons

(k) Safety factor middle platform 300 tons
(l) Reinforced testing frame top view at 300 tons

(m) Reinforced testing frame bottom view at 300 tons