

FOAM CONCEPTS, INC.

Abstract

Several thousand abandoned mine shafts exist on public land in the United States. The dangers of national park users falling into or being exposed to harmful vapors emanating from abandoned mine shafts are growing and must be avoided. Methods for mine closure, such as earthen/rock backfill, pre-cast concrete panels, steel grates or bars, timber, concrete monolithic plugs, inverted steel cones, aircraft cable woven into a grid system, and barb wire have been used in the past to address the situation. Unfortunately, all of these solutions are expensive, difficult to install at remote sites, and some have a greater probability of failure because of the weight associated with rigid structures.

Polyurethane foam as a structural material for mineshafts is an infant technology that competes against the other methods and has significant advantages associated with it. Economic savings can be realized in many ways. The foam is easier to deliver to remote sites and can be installed without having contractors traverse down the mineshaft. Installation times are very short, usually requiring only a few hours. In order to gain the confidence of agencies that are responsible for mine closures on public lands, rigorous and appropriate testing of polyurethane foam closures are required to prove or disprove the strength, reliability, longevity and cost effectiveness for the application.

The value of this study, as opposed to others, is the fact that much larger size openings were thoroughly tested. A structure of 4 ft. x 5 ft. x 9 ft. high was used in an attempt to approximate the size of the majority of abandoned mine shafts that pose a safety hazard in remote areas (Figure 10).

A distributed load 64,000 lbs. was necessary to displace the PUF closure from the walls of the mineshaft. However, it still required 44,000 lbs. to continue displacing the foam closure downward. In case of a forest fire occurring within the immediate area of a sealed abandoned mineshaft, the use of small to medium forest machines could be done with little concern for the PUF closure in terms of supporting the weight of the equipment.

The product from Foam Concepts [2] is believed to be superior to other methods that consist of heavy materials i.e. concrete or steel. Its density is only 1.3% of concrete; therefore, effects of gravity upon the structure are considerably less. The foam is essentially a plastic and therefore not effected by acid mine drainage which, is a great concern for concrete and steel closures. The expansion ratio of the foam is approximately 30:1. In situations where the opening is located in extremely difficult terrain, only one delivery of material would be required. It is found that a 30% reduction in volume of foam could be realized over that calculated from depth equations previously developed.

1.0 Introduction

Abandoned mine shafts throughout the United States present a safety hazard. Closure of these shafts is necessary in order to protect the public. Several methods of sealing the shafts are currently used, such as pre-cast concrete panels, steel grate or bars, inverted steel cones, and barbwire. These methods, however, are costly and difficult to install. Due to economic and feasibility concerns with the traditional methods, other solutions are needed. Polyurethane foam (PUF) plugs are a recent development for sealing abandoned mine shafts which are inexpensive and easily installed in remote areas.

The PUF closures have been successfully utilized for several years. Previous research has been completed on the polyurethane foam for the U.S. Department of Interior, Denver Research Center, by J.R. Harris & Company [1]. F.A. Charney, the principle author of that study, has presented design procedures for PUF closures. The information from that study has been the basis to complete new testing to further understand the behavior of the polyurethane foam when used as a structural material.

There are two methods used in applying the foam: truck mounted equipment or a self-contained system which, is delivered in 22 LB boxes. The focus of this study on the self-contained system presented by Foam Concepts [2]. The objective of this paper is to verify the structural integrity of the PUF closures if the packing materials are incorporated within the foam closure. This would then lead to a highly portable and environmentally prudent procedure for closing abandoned mine shafts.

2.0 Research Background

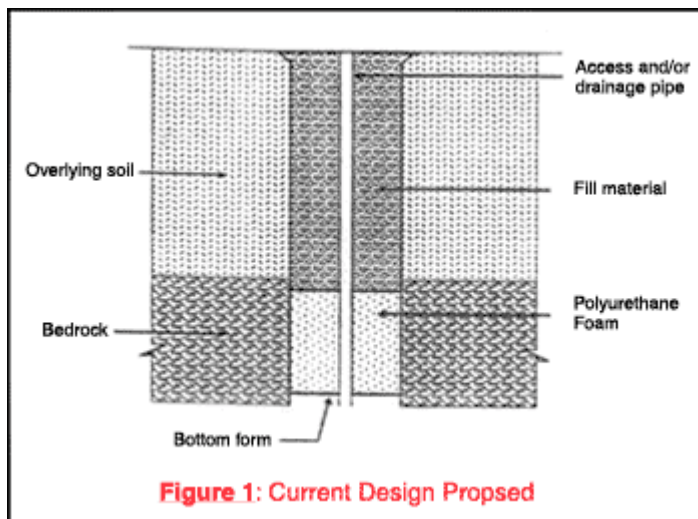


Figure 1 shows a cross sectional view of the design proposed by Charney [1]. With vertical mine shafts, a light weight plywood bottom is secured at an appropriate depth below the surface which, can often be done without traveling down the shaft. Foam is then applied, usually by truck mounted equipment, filling the upper twenty feet of the shaft. Vertical drainpipes are placed within the foam for drainage.

After the foam has set, large amounts of backfill are then applied to the top of the plug. The relatively deep soil layer above the foam closure has an arching effect associated with it and will significantly reduce the downward pressure acting on the top of the closure.

This method given by Charney [1] requires several calculations to be completed before the foam closure is installed. These calculations, shown on the next page, take into account backfill density, friction angles, and various dimensions of the opening.

1. The depth of the foam required is found using the shaft dimensions. For example, if the opening has dimensions of 4 feet by 10 feet.

$$\text{Depth} = a (2.0 + 0.5(b/a - 1))$$

$$a = 4\text{ft}$$

$$b = 10\text{ft}$$

$$b/a = 2.5\text{ft}$$

$$\text{Depth} = 4 (2 + 0.5(2.5 - 1)) = \underline{11\text{ Feet}}$$

2. The required density of the foam, with a depth to the top of foam of 50 feet and a friction angle of 30 degrees, would then be calculated as shown below:

$$a' = (2ab - a^2)/b = 2 \cdot 4 \cdot 10 - 16 = 6.4\text{ft}$$

$$a_R = h/a' = 50/6.4 = 7.81$$

$$K = \tan^2(45 - \phi/2) = \tan^2(30) = 0.333$$

$$u = \tan(\phi) = 0.577$$

$$AR = 1/(3.14u a_R K + 1) = 1/((3.14 \cdot 0.577 \cdot 7.81 \cdot 0.333 + 1)) = 0.175$$

$$\text{Density} = (0.0015 A_R \dot{\gamma} h)^{0.9} = (0.0015 \cdot 0.175 \cdot 130 \cdot 50)^{0.9} = 1.61\text{ lb. per cubic foot or pcf}$$

$$1.61 < 1.8 \text{ (1.8 is a minimum density)}$$

Therefore Use 1.8 PCF

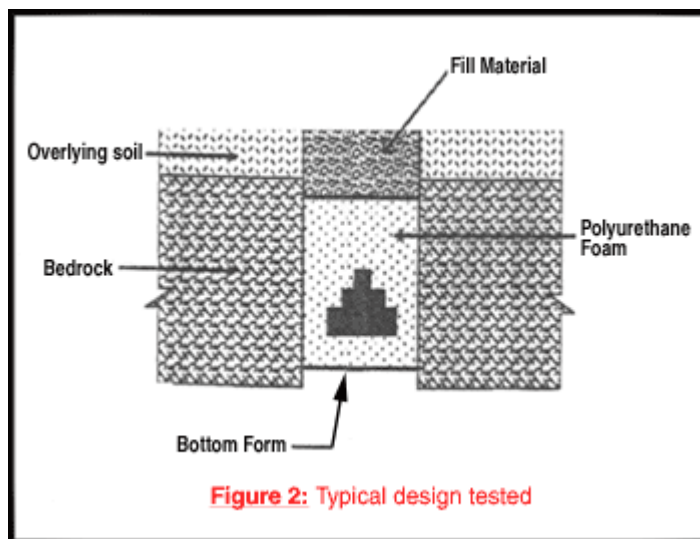
Charney [1] recommends that only densities between 1.8 and 3.0 pcf should be used. The effects of density, which will be discussed in more detail later, controls the strength of the foam in a non-linear fashion. If the foam density is doubled, the compressive strength is increased by a factor of three. Although the research done by Charney [1] has been thorough, there are a few problems that reduce the ability to implement the design from that study:

1. The truck-mounted equipment requires road access, which leaves many remote openings out of reach from large vehicles.
2. With remote sites, substantial earth moving equipment is not available. Large amounts of backfill, although quite advantageous because of the arching effect, are not easily put into place by hand.
3. Because of the many abandoned sites to be closed, if the required depth of foam for each closure could be reduced slightly, many more openings could be safely closed.

3.0 Objectives of Research

The objectives of the research were to incorporate the packing materials from the foam system by Foam Concepts [2] into the foam closure by creating a hollow core foam plug. The closure would then be engineered to use an optimal amount of foal without compromising its structural integrity. The product by Foam Concepts [2] which, was used exclusively in this research, is a self-contained system that accommodates two components sealed separately in clear plastic bags. When the foam is needed, the seal is removed and the two components are mixed together rapidly and then applied to the opening. This system has the significant advantage associated with it of being carried to the remote area in 22 lb. boxes and used when needed. The installation is not dependent upon machinery of any kind. Large openings can be closed quickly and economically because of the large expansion a curing rate of the foam. One 22 lb. box will produce 1.0 yd³ of foam.

As mentioned above, the self-contained system from Foam Concepts [2] is delivered in cardboard boxes. These boxes, which will be referred to as packing material, are presently discarded and removed from the site being filled. One hypothesis of this paper is that the packing materials can be used within the PUF closure to strengthen and there by reduce the amount of foam required in each closure. If the packing materials could be utilized within the foam, installation of the foam closures would become more reasonable because of the convenience of not having more materials to remove from the site. Figure 2 illustrates the proposed design that includes packing materials and significantly less soil placed on the foam.



The research from Charney [1] was used to provide a starting point to develop new information on polyurethane foam closures. Again, the recommended design procedures involved substantial amounts of topsoil placed upon the top of the foal plug that contributed to an arching effect which ensures a static load is applied to closure. The placement of the large amounts of soil requires heavy equipment and labor, which is usually not available in remote areas without vehicle access.

In order to reach the objective, four areas of concern were evaluated

1. Finite element analyses were completed in order to identify high-stress areas within the foam.

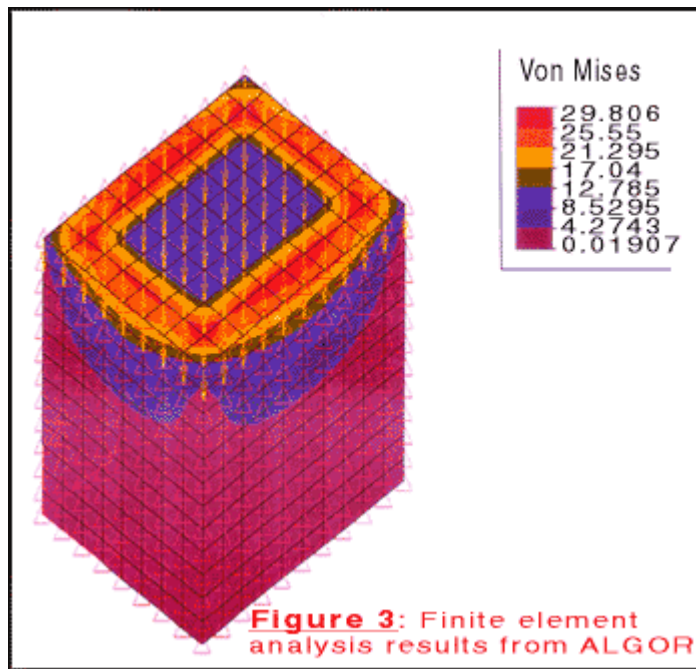
2. Material properties of the foam were identified using the American Society testing and Materials (ASTM) standards [3].

3. Small-scale mine shafts (5.67" x 7.05") were constructed to characterize closure failures. These dimensions were found from geometrically scaling the determined average opening size of 4' x 5'. Optimization techniques were then utilized to evaluate different hollow core plug designs. After an optimal shape identified, it was then possible to reduce the required amount of foam while maintaining its structural integrity.

4. Tests were conducted on more applicable size openings, 4' x 5', to verify accuracy of the small-scale tests and to more closely model actual environmental conditions.

4.0 Finite Elements Analysis

Figure 3 shows the results of the finite element analysis (FEA) and was prepared with ALGOR. As the figure indicates, high stress areas were concentrated near the top, middle sections of the plug, where as the stress decreased rapidly with depth. Using this information, analyses of box placement and foam reduction were then possible. The material properties used in this analysis are tabulated below.



1. Density = 2.5 pcf
2. Modulus of Elasticity = 107 psi
3. Poisson's Ratio = .25
4. Shear Modulus of Elasticity = 121 psi

A distributed load of 68,000 lbs. was applied to the (4 x 5 x 6) ft model, which was fully constrained in the x and y directions, but was allowed to move vertically. The stress, in pounds per square inch (psi) within the foam is shown above.

5.0 Materials Property Testing

The following material tests were done using the American Society for Testing and Materials (ASTM) [3] testing standards for rigid cellular plastics. The tests conducted were density, compression, and tension tests. All of the material testing was completed at the Colorado School of Mines strengths of materials lab.

5.1 Density Test

The purpose of the density test was to determine the density of polyurethane foam supplied from Foam Concepts [2]. The ASTM standards [3] for density tests required a minimum volume of 1.0 in³. The density test's specimens were a circular shape for the density test. The specimen's used for each test had an approximate volume of 30 in³. The results of the test are found in the table below. The mean density, of the eight samples examined, was determined to be 2.52 lb/ft³

Table 1: Density study results

Specimen	Diameter (in)	Height (in)	mass (lb.)	vol. (ft ³)	density (lb/ft ³)
1	1.56	1.58	0.00397	0.00175	2.27
2	1.56	1.48	0.00364	0.00164	2.2
3	1.64	2.07	0.00657	0.00253	2.6
4	1.59	1.64	0.00452	0.00187	2.41
5	3.91	2.75	0.0472	0.0191	2.47
6	3.91	2.67	0.0486	0.0186	2.61
7	3.75	2.11	0.0353	0.0135	2.62
8	3.75	2.48	0.0420	0.0158	2.65

Mean Density = **2.52 (lb/ft³)**

5.2 Compression Test

The purpose of the compression test was to determine the compressive strength, modulus of elasticity, and Poisson's ratio. The ASTM standards [4] for the dimensions of the compression specimen were a minimum cross-sectional area of 4 in² and a minimum height of 1-inch. The test specimens for the compression test, in this study, were of a circular shape with a radius of 2 inches and a height 2.5 in. The results of the compression test are found below. The data retrieved from the testing machines had considerable noise associated with it and was not able to be utilized in the calculation of the modulus of elasticity and Poisson's ratio.

Table 2: Results from the compression tests

Specimen	Diameter (in)	Load (lb.)	Area (in ²)	Compression strength (psi)
1	3.65	320	10.5	30.6
2	3.58	385	10.1	38.2
3	3.62	390	10.3	37.9
4	3.91	440	12.0	36.6
5	3.97	510	12.4	41.2
6	4.00	540	12.6	43.0
Mean Compression Strength (psi):				37.9

5.3 Tension Test

The purpose of the tension test was to determine the tensile strength. The ASTM dimensions [5] for the test specimens were 1 in 2 for the minimum facing area and a minimum of 1-inch for the thickness. The tension test specimens were difficult to design; three separate configurations were used.

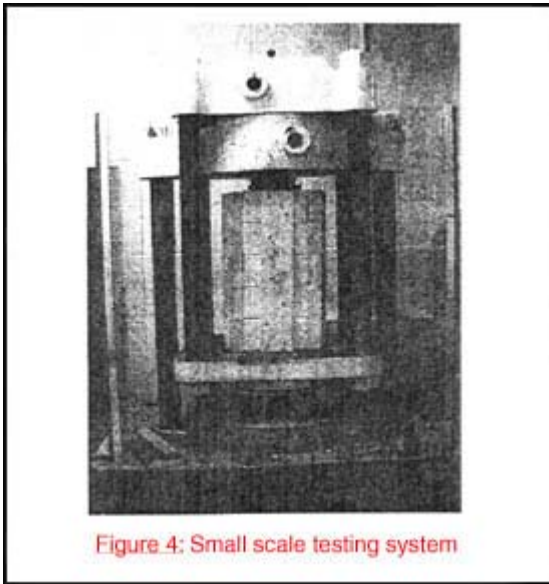
1. Initially, a square with dimensions of 2" x 2" with a height of 3 inches was constructed out of aluminum, and tested. The 2" x 2" tension specimen failed at the bonding surface between the foam and the testing apparatus.
2. Increasing the dimensions to 4" x 4" with a height of 3 inches, the bonding surface was also changed to wood. Both tension tests failed at 11 psi from the foam.
3. The 4" x 4" test specimen was again poured in order for failure to occur within the specimen and not the bonding face. The relation given by $\bar{\sigma} = P/A$ lead to reducing the middle cross-sectional area of the specimen. The area of reduction was in the shape of a rectangle with a cross-sectional area of approximately 7 square inches reduced from the total area of 16 square inches. The 4" x 4" specimen failed in the reduced area with tension strength of 17 psi.

6.0 Small-Scale Testing

The intent of the small-scale testing was to eliminate poor box placement designs and to make more efficient use of the large-scale testing time. Failure modes of the foam closures would also be better understood. In order to address the majority of mine closures, a size of 4 ft. x 5 ft. was determined to be an upper limit. The small scale testing was then accomplished by constructing geometrically reduces scale mine shafts. The length and width of the small-scale mine shaft was determined to be $b = 7.05$ in. and $a = 5.65$ in. respectively. Using the given equation [1]

$$\text{Depth of Foam Required} = a (2.0 + 0.5(b/a - 1)) \{1\}$$

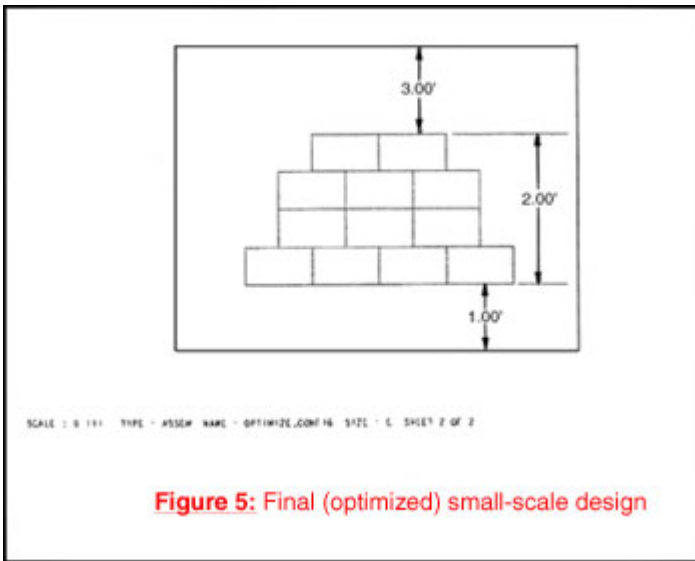
A required small-scale depth of 12-inches of foam was determined. This 12-inch depth represents 8.5 feet of foam. The experiments were designed to apply a distributed load uniformly to the top surface of the polyurethane foam. Three model shafts were then constructed out of 2 in. x 4 in. wood as shown in Figure 4. Small amounts of fill material, approximately ½-inch of dirt, were used to ensure a level interface between the loading ram and the foam. Small pieces of 1 in. x 4 in. wood were stacked in between the ram and the top of the fill material in order to displace the foam until complete failure of the closure occurred.



The first test was conducted on a foam closure without packing material positioned within the foam. This provided a standard for the following experiments given that it is the current procedure used. The failures of the solid foam plugs were quite predictable. Small portions of the uppermost layers failed in tension as the loading plate caused the foam to tear away from itself. The boundary conditions remained intact, however, and failures were not observed at the walls of the shaft.

Four preliminary hollow core plug designs were tested. Initially, attempts were made to maximize the moment of inertia in an effort to resist the bending failures, which frequently plague large rectangular closures [1]. This led to a design that is similar to the cross section of an I-beam. This design was quite unsuccessful. After incipient movement, the plug failed within the first layers of the boxes, causing large displacements and only rapid failure of any PUF closure design tested. This was due to the boxes being placed too close to the high-stress areas. Tests on the other initial designs were also discouraging and failed easily.

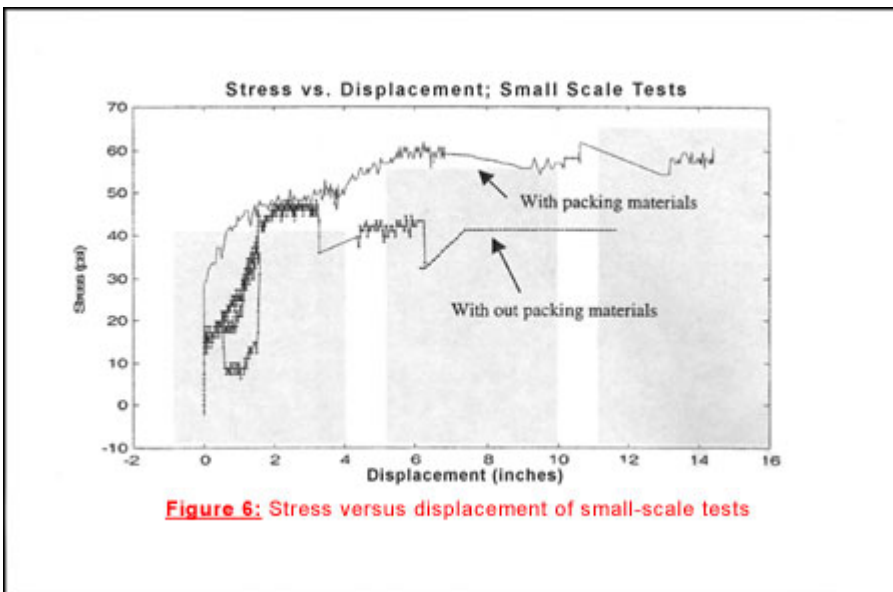
In order to give the plug designs a new direction, topology optimization was utilized to help identify a better shape. The optimization method mentioned is a graphical simulation that attempts to minimize strain energy equations that are dependant upon the boundary conditions of the system. The topology simulation gave an arched shape plug with the boxes placed in the bottom, centered within the closure resented by Figure 5.



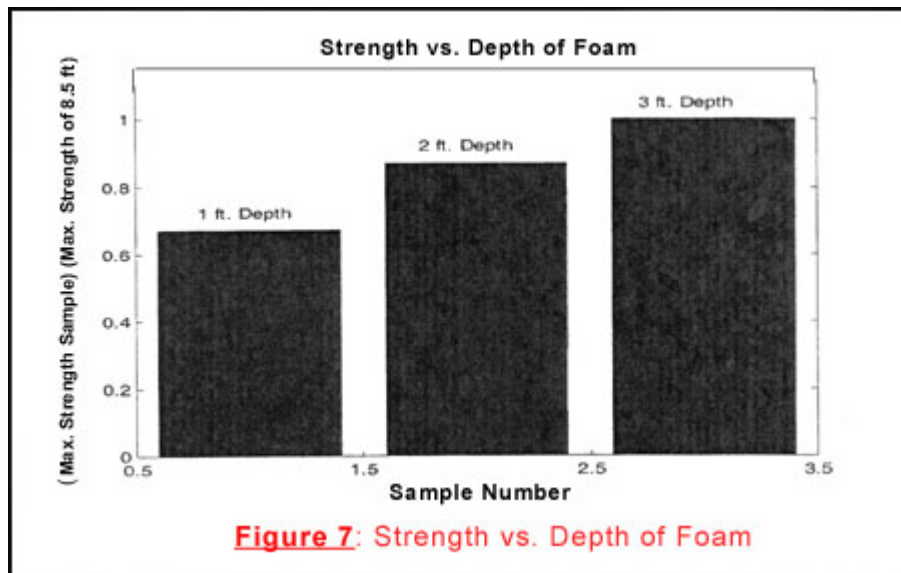
Small-Scale Testing cont'd

As shown in Figure 6 below, the maximum pressure withstood by the solid foam plug was 40 psi, whereas the optimized shape PUF closure failed at almost 60 psi. It is significant to note that a plug was considered to fail when the foam had detached completely from all four walls of the shaft. It is also important to recognize that *all* of the subsequent failures responded in a similar fashion. The entire foam closure would be pressed downward until it detached away from the walls where it would still require 10-15 psi to continue downward displacement. These failures do not occur rapidly. In every case, 25-30 minutes were required to achieve maximum downward travel of the PUF closure.

Seven tests were completed on optimized PUF closures and solid plug designs. The first optimized plug was done with the total recommended depth of 12-inches (8.5 feet). All tests conducted afterward were used to study the effects of reducing the top layer of foam found above the packing material (Figure 5).



Charney [1] states that "at a certain depth, the benefit of additional foam does not significantly reduce critical stresses, and hence, the additional material is being wasted." In an attempt to explore this phenomenon, depths versus displacement tests were completed on a small-scale basis that were representative of one, two and three foot depths of foam (figure 7) below. These plots give interesting results.



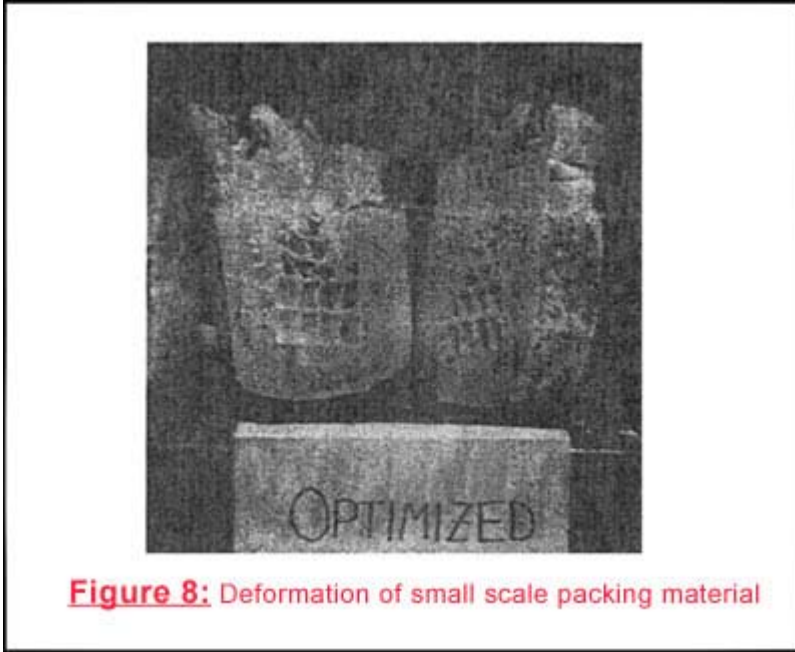
1. The 1-foot depth of foam held 53% of the stress held by the solid foam closure four more than 4 minutes before the plug sheared away from the walls and displaced downward as a whole.
2. The 2-foot depth of PUF held 87% of the stress required for failure of the solid foam closure. Failure occurred quite similar to the 1-foot depth; there was no compression of foam, and the entire closure as a whole dislodged away from the sides of the shaft.
4. It is an interesting note that the 3 feet of foam failed at the same pressure, 100%, of the small-scale solid PUF closure, which contained a representative 8.5-feet of solid foam. This clearly indicated that after approximately 3 ft. of depth, the foam would compress and fail in tension tearing away from itself before the foam as a whole dislodges from the walls and travel downward.

6.0 Small-Scale Testing cont'd

The findings from these tests show the required depth of solid foam, above the packing material, to be 3 feet in depth. This equates to an overall depth of 6 ft. of foam, 3 ft. of solid foam above the packing material and another 3 feet encasing the packing materials. Which is 70% of the material used in previous recommendations.

After constructing a small-scale PUF closure to these specifications, the mode of failure was changed. At 40 psi the foam displaced as expected through the top solid foam layer, similar to the solid foam plug, until the compressed foam approached the packing material. At this point, all downward travel stopped. The PUF closure would then support the approximate 40-psi over a period of several minutes. The pressure increased and the plug eventually failed at 60 psi, shearing away from all four sides and displacing as a whole downward at a lower pressure of 10-15 psi. The behavior

was easily repeated three more times. As figure 8 (below) indicates, it appears that the top layers of boxes were quite deformed, whereas the lower two layers show little sign of damage. There are two hypotheses that would initially explain this behavior. First, it could indicate that the applied force is redirected at an angle in towards the walls instead of normal to the face of the foam; this however, is not entirely logical. Why would removing material -- essentially adding a hole -- make the closure stronger? The second hypothesis is that it appears that restricting its area changes the density of the foam. Density changes would have to be confirmed before an explanation could be reported.



7.0 Description of Large-Scale Testing

The value of this study, as opposed to others, is the fact that much larger size openings were thoroughly tested. Many previously unknown variables could be addressed due to this part of the study, such as the following:

1. The assumption made in the study by Charney [1] that the foam is homogeneous and therefore stress would be a linear function with respect to the area of the opening.
2. The fact that most PUF closures are not back filled with large amounts of material.

The most important question addressed, however, was if the large-scale tests would demonstrate that the "optimized" hollow core plug would behave in a similar manner as that of the small-scale tests and possess greater strength? A structure of (4x5x9) feet high was used in an attempt to more closely replicate the size of the majority of abandoned mine shafts that pose a safety hazard in remote areas (Figure 9). Logs with an approximate diameter 13-inches were used to construct a form in which compression tests could be conducted on the foam. Four 5/8-inch diameter threaded rods were placed at the corners in order to secure the assembly together.

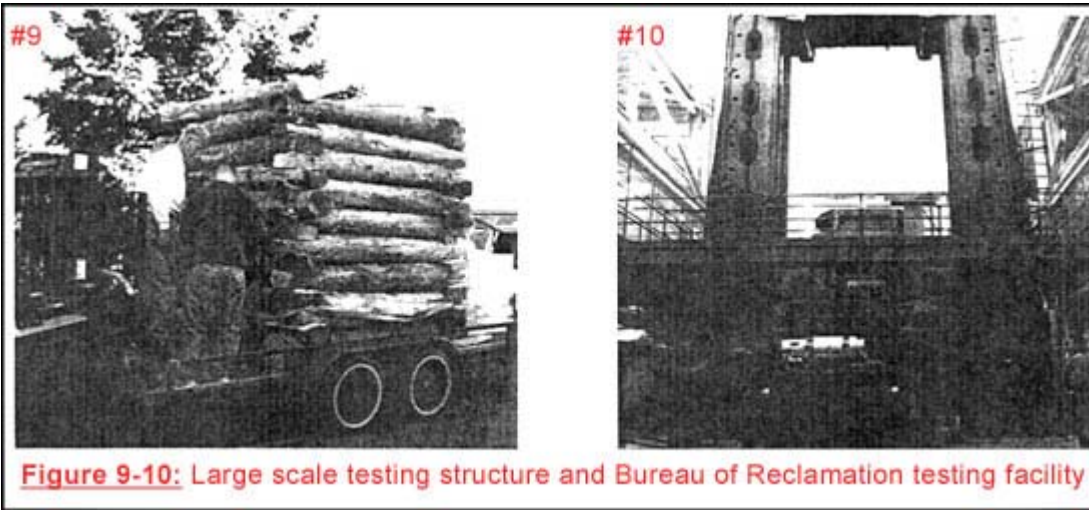


Figure 10 shows the 5 million-pound press located at the Denver office of the U.S. Bureau of Reclamation (BOR) Materials Engineering and Research Laboratory managed by David W. Harris, Ph.D., P.E. that was used to apply large compression stresses to the PUF closures in a similar manner to the small-scale tests:

1. The polyurethane foam was cast inside the log structure.
2. Approximately 10-12 inches of loose soil with a small number of roughly 1-inch size stones were used as fill material, which was used to create a uniform and level surface.
3. A loading platform was then placed on top of the fill material.

7.0 Description of Large-Scale Testing cont'd

During each test, the load was applied in the same fashion while the displacement of the loading ram and applied load was recorded. Pressure sensing devices were constructed in order to identify high stress areas within the foam. Bladders which consisted of ½ -inch diameter tubing were filled with water, reduced in size to 1/8 inch tubing, and connected to TO560G3 Omega (0-60 psi) pressure transducers in an attempt to identify pressures at different locations within the foam. These sensors worked on the premise that as the load was applied, a small volume of water would be displaced out of the bladders placed within the foam, travel through the 1/8 inch tubing and create a pressure difference outside of the PUF closure. The pressure transducers were then able to read varying amounts of stress at key locations within the foam. The sensors were placed as shown in figure 11. Figure 13 presents the data obtained from the transducers.

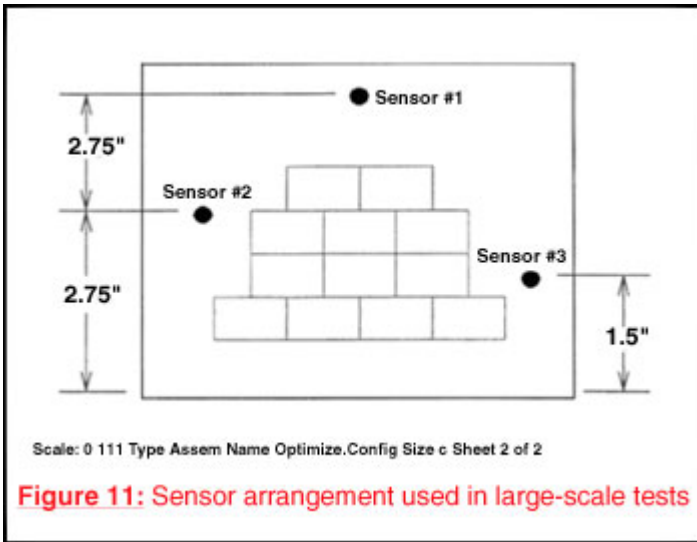


Figure 11: Sensor arrangement used in large-scale tests

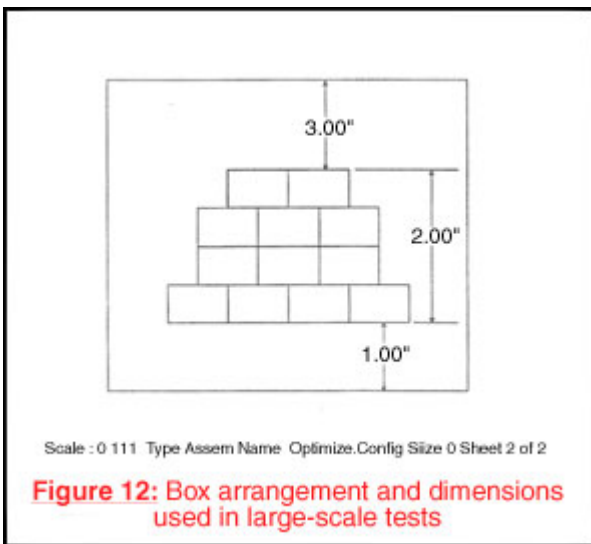


Figure 12: Box arrangement and dimensions used in large-scale tests

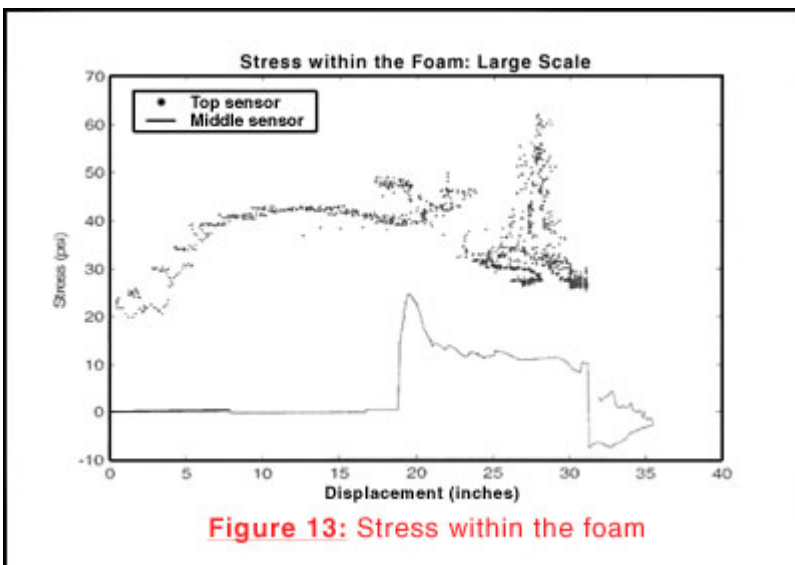
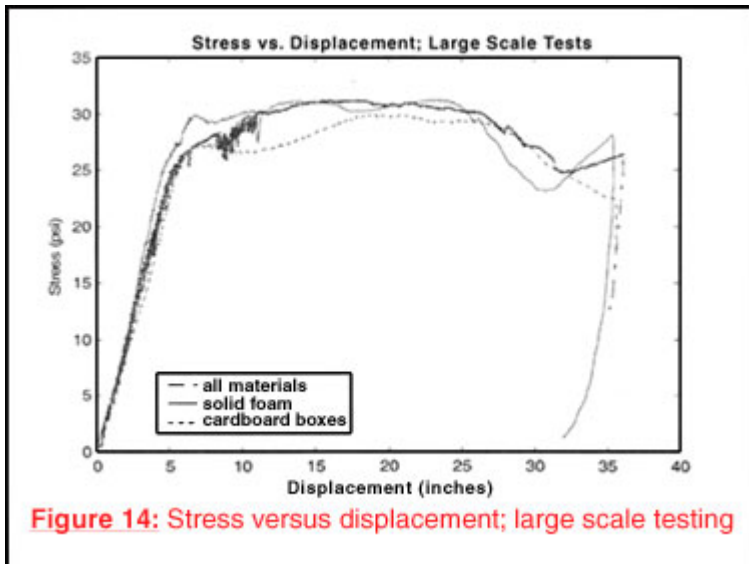


Figure 13: Stress within the foam



The loading scenario for each test was as follows: first, a load of 42,000 lbs. Was applied over a five-minute time span or 8,400 lb./min. After this was reached, another 20,000 lbs. was applied over five more minutes. Noticeable movement began in all three tests at approximately 62,500 lbs.

Comparing the large and small-scale solid foam closures show that just increasing the size of the opening reduces the strength of the foam. There was a difference of 10 psi between large and small-scale solid foam tests. This would seem to contradict the assumption of scaling the stress linearly with the size of the opening that made in earlier research [1].

The large-scale tests also revealed another piece of information. All three tests, one with solid foam and two that incorporated the packing materials, failed at approximately 30 psi with or without packing materials. In the first test, boxes were placed in the same location as the small-scale model that indicated an increased strength (Figure 12 above). Along with that, the empty mixing bags, which contained foam, were also placed in the middle of the opening and stacked on top the upper layer of packing materials. Where as the second test performed with packing material consisted of the boxes placed in the usual arrangement without the bags. Both of these tests were well within the strength of the solid foam closure, which was also tested (Figure 14 above).

8.0 Conclusion

The results from the large-scale tests were quite encouraging; the effect of the packing materials, if placed in the correct position, was minimal. A distributed of 64,000 lbs. was necessary to displace the PUF closure from the walls of the mineshaft. However, it still required 44,000 lbs. to continue displacing the foam closure downward. In the case of a forest fire occurring within the immediate area of a sealed abandoned mineshaft, the use of small to medium forest machines could be done with little concern for the PUF closure in terms of supporting the weight of the equipment. The operating weights of various machinery, used for moving large amounts of materials, are listed below for comparison.

- | | |
|--|-------------|
| 1. Komatsu - bulldozer (D21P-7) | 9,220 lbs. |
| 2. Caterpillar - backhoe loader (466B-3114T) | 19,603 lbs. |
| 3. Caterpillar - track type loader (D79 LGP) | 67,472 lbs. |
| 4. Caterpillar - log loader (330BLL) | |

Even if the log loader was used for fire fighting support, with a track length of 9.5 feet, only half of the machine could be on top of the closure at one time. Although the effects of soil arching are significant in raising the compressive strength of the closure, the distributed load held by each large scale PUF closure in this study exceeds the strength requirements needed for safe closure of abandoned mine shafts. Both large-scale tests, with packing materials, were completed on specimens that used only 70% of the suggested depth from Charney [1]. This indicated that new procedures can be developed in order to safely and more economically close more mineshafts that are located in remote sites.

Longevity of the closure is also a concern when addressing remote sites that are difficult in reaching by vehicle. When compared to alternative shaft closures of concrete and steel, the foam has no corrosion or chemical deterioration from acid rock generation in a typical sulfide environment. The following information is from various publications on the use of polyurethane foam in closing mineshafts:

1. "Advantages off using polyurethane foam include ease of installation, minimum disturbance to surrounding ground, durability and availability through existing contractors." [6]
2. "Polyurethane foam has been used in the mining industry for almost 20 years. Its primary application has been as a grout for reinforcing rock strata and helping control water leaks in mines. When polyurethane is injected under pressure into mine strata, it fills the cracks, adheres to the rock and bonds the broken strata together. Additionally, filling the cracks with the nearly impermeable foam creates an effective water barrier." [6]
3. "Polyurethane foam is extremely resistant to chemical decomposition. Although an extremely toxic solvent is on the market which will dissolve polyurethane, this solvent would never accidentally come in contact with polyurethane used in mine closures. **For all practical purposes, only two things will chemically break down polyurethane foam; ultraviolet light and fire.**" [Note: both sunlight and fire are prohibited from contact through proper backfilling over the shaft installation of rigid foam.] [6]

8.0 Conclusion Page cont'd

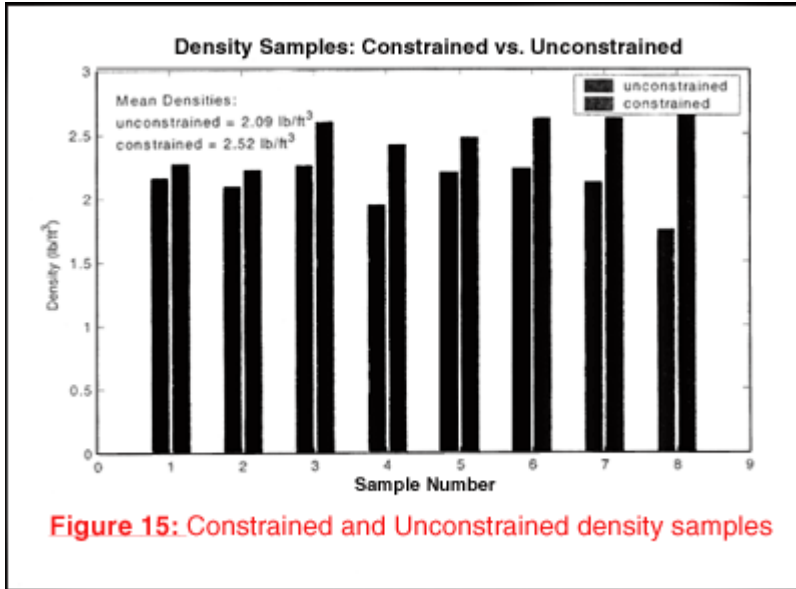
Efforts were made to address the differences found in comparing the large and small-scale compression tests. After returning to the ASTM [3] standards, for completing density studies, only a minimum volume was specified for the foam to be cast into. A second density study was then performed in order to verify hypothesis that the area used for casting would influence the density of the foam. As figure 16 indicates, two different containers were used to cast each density sample.

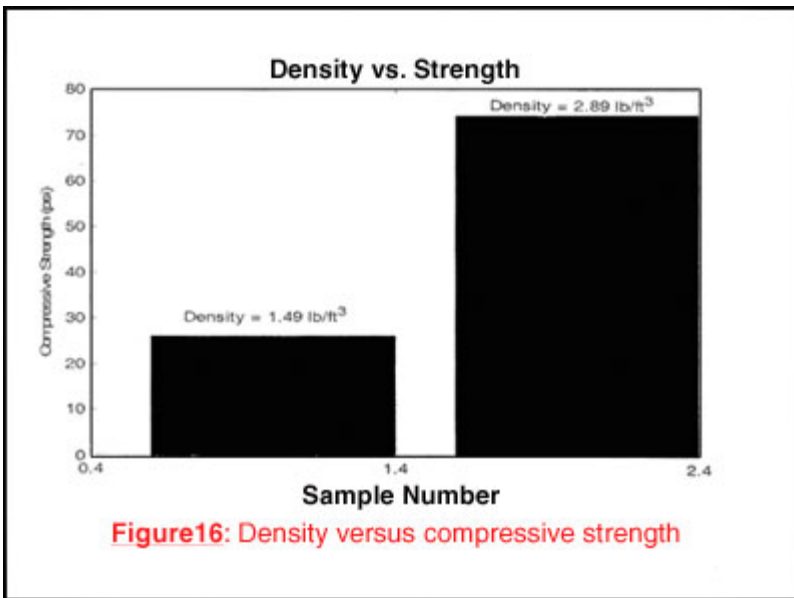
1. A wide and flat container similar to a baking pan, which represented the unconstrained density values.
2. A narrow and tall geometry was used for the second density test. This container would represent the constrained density values.

As the legend indicates, the unconstrained density test was 80% of the constrained values. Density studies were performed at great length in the research done by Charney [1]. The results from this research are shown in Figure 16. The two samples shown in Figure 16 closely match the densities used in this study. If the density could be increased enough, the compressive strength will also increase. This explains the difference the in maximum stress between large and small-scale tests.

When packing materials were placed inside the small-scale models, they are for the foam to be cast into was greatly reduced and thereby increasing the density and strength in the lower sections. With the larger opening, the packing materials did not influence the density of the foam enough; therefore, the compressive strength was not changed.

Keeping the density level at a level high enough to support large loads is a much greater concern when very large openings need to be sealed with polyurethane foam. Samples at the site should be taken to ensure the density is at least 2 pounds per cubic foot (pcf).





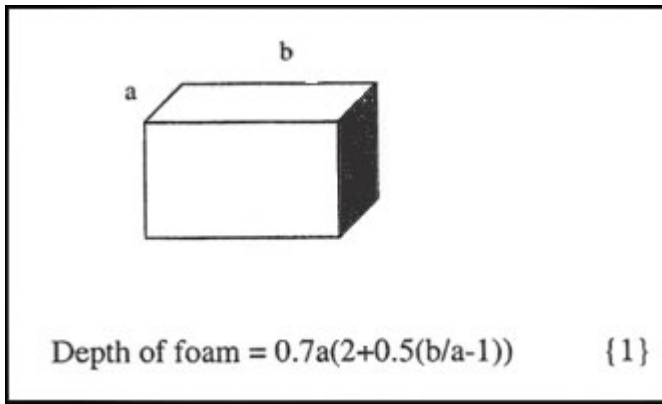
The product from Foam Concepts [2] is believed to be superior to other methods that consist of heavy materials i.e. concrete or steel. Its density is only 1.3% of concrete; therefore, the effects of gravity upon the closure are considerably less. The foam is essentially a plastic and therefore not effected by acid mine drainage, which is a great concern for concrete and steel closures. The expansion ration of the foam is approximately 30:1. In situations where the opening is located in extremely difficult terrain, only one delivery of material would be required. Installation times are also very short, three to four hours in most cases, without requiring extensive site preparation.

Poisson's ratio is also a considerable advantage. With the PUF closure, almost half of the force exerted on the top of the closure is transferred to the sides of the mineshaft, which help to resist further movement. The PUF closure behaves similar to that of a cork inside a bottle.

9.0 Recommendations Regarding PUF Closures

As mentioned in the introduction of this report, the basic objective of the research was to develop rational and safe procedures for placing packing materials inside polyurethane foam closures of reasonably sized openings located in remote locations. On the basis of both large and small-scale testing, the following recommendations can be made to append current design procedures [1].

1. In the case of average size openings or smaller, roughly 4ft x 5ft or smaller, the depth equation given by Charney [1] can be reduced by 30% which is shown below. This is only valid with a b/a (longest side/shortest side) ratio of less than 3.



2. Packing materials can be safely placed in the middle, lowest sections within the foam as shown in [Figure 12](#). The boxes must be fastened together into a triangular (pyramidal) shape making an effort to minimize height and placed on top of the first foot of foam cast. It is also imperative to maintain a zone, or perimeter, of solid foam around the packing materials of at least 18 inches.
3. The area between the rock face and the packing materials is crucial to the strength of a PUF closure. If cracks are present after casting a layer of foam, any effort necessary to fill these cracks with additional foam should be made: continuity of the foam is crucial.
4. In closing large openings density changes will become more important. The larger the volume of the area to be cast into, the lower the density becomes, thus lowering the compressive strength of the foam. Do not reduce the depth equation as suggested above for these cases or situations where the ratio of b/a is greater than three (3).
5. Large amounts of soil are not necessary for remote locations. Two (2) to three (3) feet of soil placed on top of the closure will be sufficient for protection from sunlight and fire. It is necessary, however, to ensure drainage above the PUF closure in order to retain the back fill placed on top of the polyurethane foam.
 5. The drainage pipe is a 2-3-inch diameter PVC pipe suspended along the side of the shaft and passing through the wire/plastic tarp bottom from which is also just suspended at the corners by nylon rope and attached to stakes or fence posts or anything nearby. It is off-center and not in the way of the boxes. The pipe will keep water off the foam and prevent water penetration over time by eliminating the freeze thaw cycle. In addition, the pipe will vent air pressure build-up in the mineshaft from a rise in water level in the shaft (these changes are cyclical depending on long-term as well as short-term weather patterns). Also, if there is a rock collapse which compresses air, it allows pressure release through the vent pipe and won't jar the plug. Some shafts may have water rise to the level of the plug instead of popping the plug like a cork [7].

10.0 Future Needs

Although the static load tests reported herein have been extensive, uncertainties still remain in identifying the behavior of polyurethane foam closures. The effects of a phenomenon known as creep have not been successfully recorded. All materials,

Under the right environmental conditions (particularly at elevated temperatures), slowly creep (deform) under stress levels well below the yield point determined from testing.

It would be a considerable addition in continuing the study of polyurethane closures if conveniently located mine openings were identified and sealed using the procedures recommended above. The amount of deformation of long periods of time could then be accurately studied and documented. To this date only a few failures of PUF closures have been reported; however, these failures occurred because of rock facing motion or collar collapse and not due to the failure of the foam. Placement of the plug into solid bedrock should eliminate this type of problem.

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