DESIGN AND ANALYSIS OF A NEW METHOD TO TEST MINE SEALS

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ABSTRACT

The final rule for mine seals issued in 2008 increased the seal design strength and specified new requirements for the engineering and construction of mine seals. New seal designs must resist a design pressure-time curve, remain elastic to withstand repeat overpressures, have adequate anchorage to the surrounding strata, and consider roof-to-floor convergence. Historic requirements for seal design only required a seal to survive a 20-psi test explosion at the National Institute for Occupational Safety and Health (NIOSH) Lake Lynn Experimental Mine (LLEM) without any visible structural damage and within certain leakage bounds. The explosion test methods used in the past to judge the adequacy of seal design did not consider many factors important for seal designs that meet the new standards. New seal testing is needed to consider:

1) Seal construction material
2) Foundation conditions
3) Hitching conditions
4) Roof-to-floor convergence

Researchers designed and are building a seal test fixture for use in NIOSH's Mine Roof Simulator (MRS), which is a large biaxial loading frame capable of applying a vertical load up to 3,000,000 lb and a lateral load up to 1,600,000 lb. The fixture uses the vertical loading capability of the MRS to simulate roof-to-floor convergence and its shear loading capability to apply a load to the face of a seal test specimen, which is set in foundation blocks to simulate roof and floor conditions. The seal test fixture consists of two opposing triangular frames that apply a 4-point bending and shear load to the test seal face. NIOSH researchers performed simple analytic and finite element method analyses of each structural member and obtained excellent agreement. At maximum design load of 900,000 lb, the lowest safety factor is 1.15 which is acceptable for a testing fixture.

The seal testing program will examine four factors above affecting seal performance. The seal test specimen permits four failure modes: (1) bending and tensile failure through the seal structure, (2) shear failure through the seal foundation, (3) shear failure along the seal-foundation interface, and (4) shear failure through the seal. Researchers from the U.S. Army Corps of Engineers (USACE) and NIOSH are working to create a new software version of the Wall Analysis Code specifically for Mine Seals (WAC-MS) for application to mine seal design and analysis. Successful completion of the testing matrix will provide validation data for the resistance functions in WAC-MS and for other numerical design tools used for mine seals.

1 INTRODUCTION

1.1 BACKGROUND

Seals are used in underground coal mines throughout the United States to isolate abandoned mining areas from the active workings. Prior to the Sago Mine disaster in 2006, mining regulations required seals to withstand a 20-psi explosion pressure. On April 18, 2008, the Mine Safety and Health Administration (MSHA) issued “Sealing of Abandoned Areas; Final Rule” which increased the seal design strength and imposed new requirements for the engineering and construction of mine seals [1]. In response to the new mine safety regulations, researchers at NIOSH, in collaboration with researchers at the USACE, are engaged in efforts to improve seal design through better understanding of seal failure mechanisms and improved engineering methods that account for the seal foundation and roof-to-floor convergence in the mine. This report describes a new seal testing program that will provide essential validation data for mine seal analysis and design methods.

1.2 LEGAL REQUIREMENTS FOR SEAL DESIGN

In the final rule [1], seals must:

1) Withstand 50 psi if the sealed area atmosphere is monitored and maintained inert;
2) Withstand 120 psi if the sealed area atmosphere is not monitored; or
3) Withstand greater than 120 psi if the sealed area atmosphere is not monitored and certain conditions exist that might lead to higher explosion pressure.

The duration for these pressure loadings is 4 seconds, and the rise time for the pressure is either instantaneous, 0.1 second for 50 psi, or 0.25 second for 120 psi depending on the purpose of the seal. 30 CFR §75.335(b)(1) specifies the content of an engineering design application for seals that shall "address gas sampling pipes, water drainage systems, methods to reduce air leakage, pressure-time curve, fire resistance characteristics, flame spread index, entry size, engineering design and analysis, elasticity of design, material properties, construction specifications, quality control, design references, and other information related to seal construction." MSHA provided additional information for seal design applications in "Guidelines for Seal Design Application" [2]. From select information in these guidelines, the seal design application should:

1) Specify which pressure-time curve from the Final Rule is being used in the design.
2) Provide a complete set of engineering calculations on which the design is based.
3) Specify the elastic nature of the design and its ability to withstand repeat overpressure applications.
4) Provide information pertaining to the site location and site preparation.
5) Specify any ground remediation that might need to occur for the site to be acceptable for seal design.
6) Specify the minimum strata strength requirements for the seal design and the means by which this strength should be determined.
7) Provide information pertaining to the anchoring of the seal.
8) Specify frequency of examining for convergence and actions to be taken if maximum convergence is exceeded.

In addition to the engineering requirements for mine seals, the final rule also requires quality control and accountability throughout the design, construction, and operation of mine seals.

30 CFR §75.335(b)(1) specifies that engineering design applications be certified by a professional engineer. 30 CFR §75.335(c)(2) requires a professional engineer to certify that the approved seal design is applicable to conditions at the mine. Finally, CFR §75.337(d) requires that "upon completion of construction of each seal a senior mine management official, such as a mine manager or superintendent, shall certify that the construction, installation, and materials used were in accordance with the approved ventilation plan."

MSHA provided additional clarification on these responsibilities in "Sealing Abandoned Areas in Underground Coal Mines – Compliance Guide Questions and Answers" [3]. According to the compliance guidelines, "the professional engineer must certify that an engineering design application is in accordance with current, prudent engineering practices and that the seal design is applicable to conditions in an underground coal mine." Also, "the professional engineer must be present for a sufficient amount of time to (1) verify that the seal application is suitable for the specific conditions; (2) confirm that the site preparation is adequate; (3) confirm that the workforce is adequately trained to properly build the seals; (4) verify that the correct materials and procedures are being used to construct the seal; and (5) confirm that adequate quality control measures are in place and are being followed."

30 CFR §75.335(b)(2) specifies the content of a seal design application based upon a full-scale explosion test or equivalent means of physical testing. The final rule and supporting guidelines do not specify the nature of the applied pressure-time curve for the full-scale testing. Presumably, this test curve must meet or exceed the characteristics of the design pressure-time curves for an engineering seal design application under 30 CFR §75.335(b)(1). The application must address differences between the seal support during test conditions and the range of conditions in a coal mine. The testing and design requires certification by a professional engineer, and as before, the same requirements apply for quality control and accountability throughout the design, construction, and operation of the mine seals.

1.3 EXAMPLES OF APPROVED SEALS

Under the new final rule on seals, MSHA has approved a number of seal designs and posted characteristics of the approved seals on its website. Table 1 summarizes a selection of approved seals designed to meet the 120 psi pressure-time curve with instantaneous rise time. For the comparison, the seal dimensions are 20-ft-wide by 8-ft-high. Construction materials are (1) reinforced concrete, (2) unreinforced concrete, (3) cementitious foam concrete, or (4) polyurethane foam and aggregate between concrete block walls. Table 1 compares the seal thickness, anchorage requirements, and design convergence limit for each seal design.

Table 1 – Summary of approved seal designs for 120 psi pressure-time curve with instantaneous rise time. Seal dimensions are 20-ft-wide by 8-ft-high [4].

Construction material	Thickness	Reinforcing bar	Anchorage Requirements	Convergence limit
3,000 psi concrete	28 in	#9 bar and others	#9 bar 18 in deep	Not known
3,000 psi concrete	8 ft 11 in	None	Friction only	Not known
3,000 psi concrete	9 ft 10 in	None	Friction only	0.192 in (0.2%)
400 psi cementitious foam concrete	15 ft	None	Friction only	19.2 in (20%)
Polyurethane foam and aggregate core with concrete block walls	51 in core 66.5 in total	None	Friction only	2.5 in

The designers for these approved seals apparently used numerical analysis methods such as finite element method or simple analytic methods such as a plug design formula in developing these designs. NIOSH researchers note that none of the design methods have ever been validated with mechanical testing at the pressure levels required in the new final rule for seal design.

1.4 OBJECTIVES

In recognition of the need for experimental validation of seal designs approved under the new seal regulations, this paper describes the mine seal test experiments underway at NIOSH. The paper provides a review of prior seal testing conducted at NIOSH's Lake Lynn Experimental Mine. Based on requirements of the new seal regulations, new testing requirements are defined. To conduct the proposed tests, the design and analysis of a testing fixture for use in the Mine Roof Simulator at NIOSH is presented. The paper concludes with a description of the seal test program, the expected results, and their application. Construction of the test fixture is presently underway, and researchers are expecting the first results in 2010.

2 SUMMARY OF PRIOR SEAL TESTING

2.1 HISTORIC REQUIREMENTS FOR SEAL DESIGN

The Federal Coal Mine Health and Safety Act of 1969 required mined-out areas to be ventilated or sealed with "explosion-proof bulkheads" that were to be constructed with "solid, substantial, and incombustible materials." Mitchell [5] reviewed experimental and actual mine explosions and concluded that a seal may be considered "explosion-proof" if it is designed to withstand a static load of 20 psi. Prior to 1992, the Code of Federal Regulations lacked a definitive engineering design specification for explosion-proof seals. Stephan [6] provided technical justification for what became the 20 psi standard based in part on investigations of underground coal mine explosions in the active workings between 1977 and 1990 and in part on Mitchell's earlier recommendation. Thus, in the 1992 rule change to 30 CFR §75.335(a)(2), the explosion pressure performance criterion for seals became 20 psi.

The 1992 seals rule recognized two types of seals, namely, the Mitchell-Barrett seal which was constructed with two rows of solid concrete blocks with mortar between all joints, and the alternative seals which were made from different materials such as shotcrete with reinforcement bars, cementitious foam concrete, polyurethane foam and aggregate mixtures, lightweight cementitious foam blocks, and wood cribs. The 1992 seals rule did not specify a pressure-time curve for the design of seal structures, nor did it specify anything about the seal foundation, air leakage, water drainage, roof-to-floor convergence, or other engineering considerations. The 1992 rule did require some quality control for the construction materials or the construction procedures, such as compressive strength testing of materials used. The basis for MSHA approval of any alternative seal design concept was an explosion test conducted by NIOSH at the Lake Lynn Experimental Mine (LLEM). If a candidate seal design survived a 20-psi test explosion at LLEM without any significant visible structural damage and within certain air leakage bounds, it was approved for use throughout the coal industry.

During the period 1992 through 2006, MSHA approved seals in 6 broad construction categories based on explosion tests conducted by NIOSH at LLEM [9].

Category 1 included those seals made of concrete or concrete-like materials such as shotcrete or gunite with internal steel reinforcement and anchorage to surrounding rock via additional steel reinforcement bars.

Category 2 included the so-called “pumpable” seals constructed with different thicknesses of pumpable cementitious material depending on its compressive strength. Category 2 seals did not contain internal steel reinforcement and were not hitched to the surrounding rock; they were held in place through friction between the seal material and the rock.

Category 3 seals were “articulated” structures made of discrete concrete blocks, either solid or hollow core, which may or may not be hitched to the surrounding rock. Seals in this category were the standard solid-concrete-block seal which required hitching and the solid-concrete-block seal with pressurized grout bags which did not require hitching to withstand 20 psi.

Category 4 seals were made from polymer materials mixed with dry, crushed limestone aggregate, ranging in size from ¼ to 1 in, placed between two, dry-stacked, hollow-core or solid-concrete-block form walls. This seal did not require hitching.

Category 5 seals were made from stacked wood crib blocks nailed together with 4-in-long nails. These seals, used where high convergence was expected, required hitching into the surrounding rock.

Category 6 seals were made from lightweight cementitious foam blocks cemented together with an MSHA-approved bonding agent. Lightweight block seals constructed 24- or 32-in-thick required hitching; whereas lightweight block seals more than 40-in thick did not require hitching.

2.2 EXPLOSION TEST METHODS APPLIED TO PRE-2006 MINE SEALS

The structural tests on coal mine seals were conducted at NIOSH’s Lake Lynn Laboratory (LLL), which is a multipurpose research laboratory designed to provide a modern, full-scale, realistic environment for surface and underground research in mining health and safety technology [7; 8]. NIOSH researchers utilized four distinct test procedures [9] for conducting tests on 20-psi seals and each procedure subjected the test seal to different loading conditions as follows:

1) Explosion tests on seals in crosscuts loaded seals with the static blast wave overpressure that is non-uniform across the tested seal face.
2) Explosion tests on seals in C-drift loaded seals with the reflected blast wave overpressure that is assumed uniform across the seal.
3) Hydrostatic chamber tests using water pressure loaded seals with a static pressure that is nearly uniform across the seal.
4) Hydrostatic chamber tests using methane-air explosion pressure loaded seals with a static overpressure that is assumed uniform across the seal.

Figure 1 shows the explosion test area in the multiple-entry section of LLEM. For most of the tests, the seals were built in crosscuts 1, 2, and 3 between B- and C-drifts. The explosion originated at the closed end of the C-drift, and the blast wave propagated down the drift and loaded seals located in crosscuts perpendicular to the direction of the main blast wave. This test procedure induced a non-uniform, static pressure that swept across the seal face as the pressure wave propagated down the entry.

In a few explosion tests, the seal was constructed across the C-drift between cross-cuts 3 and 4. The test explosion began at the closed end of the C-drift, and the blast wave subjected the seal to a “head-on” pressure loading. This test procedure induced a reflected blast wave overpressure on the seal face that is assumed uniform.

Figure 2 is a schematic of a hydrostatic chamber at LLEM used by NIOSH researchers to impart pneumatic, hydrostatic, or methane-air explosion pressure on test seals. Figure 2 shows the test seal in front of a dead-end section of tunnel excavation, the support steel surrounding the perimeter of the seal to simulate hitching, and the pressurization system using high pressure water, compressed air, or some combination of the two. Sapko et al. [10] describe the large and small hydrostatic test chambers at LLEM in greater detail. The hydrostatic chamber tests using either water pressure (type 3 test) or methane-air explosion pressure (type 4 test) applied a static pressure across the seal face. In both test procedures, the pressure on the seal face is assumed uniform.

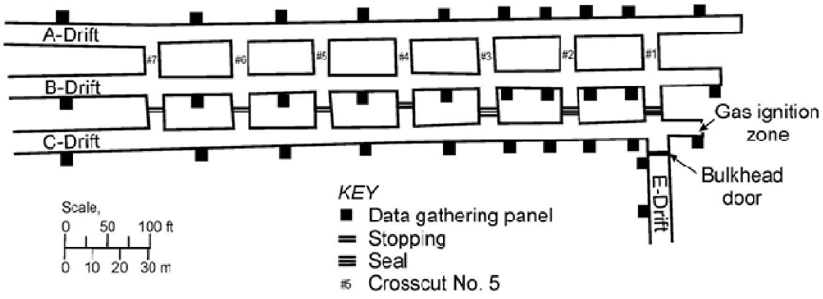

Figure 1 – Plan view of the LLEM showing the multiple entry area and the seal and stopping locations. The first crosscut, designated as “#1”, is nearest the dead-end of drifts A, B, or C [9].

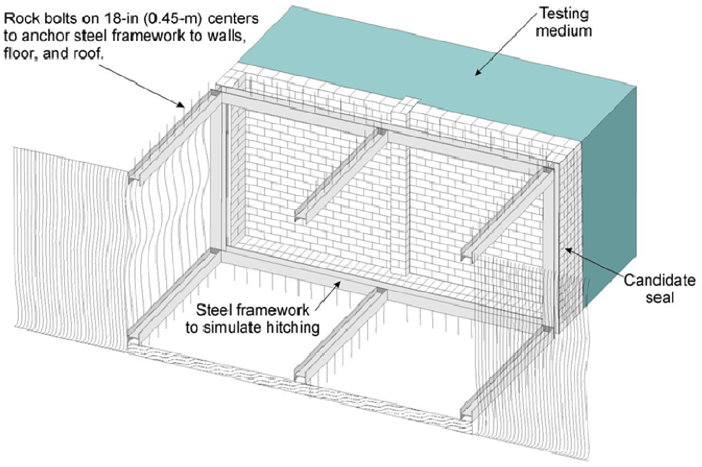

Figure 2 – Schematic of the hydrostatic chamber [10].

2.3 SHORTCOMING OF PRIOR SEAL TESTS FOR NEW SEAL DESIGN REQUIREMENTS

The prior seal testing methods have shortcomings with loading conditions, foundation and hitching conditions, and convergence considerations with respect to the new engineering requirements for seals in the final rule [9]. The loading conditions for the existing test data are inadequate for the new seal design requirements owing to the magnitude, rise time, duration, and uniformity of the test explosion pressure.

The highest pressures developed by the prior explosion tests rarely exceeded about 100 psi and the vast majority of tests only subjected the test seals to less than 25 psi. While this pressure magnitude was adequate for the old standard, new testing methods should apply pressure commensurate with the new standard.

The rise time for the pressure wave from the prior explosion tests was on the order of 0.01 to 0.1 seconds and is considered “slow” for the structural analysis of mine seals. At this pressure rise rate, the dynamic load factor on the structure is 1, which means that the equivalent static load on the structure is equal to the transient dynamic load. In the new standard, the rise time for the pressure time curve is instantaneous, which means that the equivalent static load on the structure is two times the transient dynamic load. If the design pressure-time curve has a peak value of 120 psi, the equivalent static pressure is 240 psi.

The duration of the pressure load from explosion tests conducted prior to the new seals regulation was generally less than a few tenths of a second and is much less than the required 4 second duration as specified in the final rule. The prior explosion tests only filled up to 85 feet of entry at LLEM with an explosive gas mixture, which is small compared to the gas volume that could ignite within a sealed area. Small explosive gas volumes will generally result in lower pressures, slower rise times and shorter durations compared to large explosive gas volumes.

Finally, most of the existing explosion seal tests applied a nonuniform, “sweeping” pressure across the seal face. This complex pressure loading condition is difficult to analyze with structural analysis methods, and the structural data so obtained is not readily amenable for validating numerical design methods.

The roof, rib, and floor rocks at LLEM are strong limestone. Thus, foundation conditions for seals tested at LLEM by either explosion or hydrostatic tests can be described as “rigid” or “unyielding” and represent best-case circumstances. The foundation conditions for the existing seal tests at LLEM do not represent typical conditions found in underground coal mines where the roof and floor rock and the coal ribs may have lower stiffness and strength. Only a few of the existing explosion seal tests were actually hitched by excavating into the floor and rib rocks. In most tests where seal designs required hitching, it was simulated with angle iron bolted to the floor and rib rock.

Finally, existing seal test procedures, explosion or hydrostatic, do not examine the effects of convergence on the performance of seals and their ability to resist the design pressure-time curve when subject to some degree of roof-to-floor convergence. Seal design that considers convergence is a new engineering requirement specified by the final rule. The structural performance of seals subject to convergence has never been evaluated through testing.

3 NEW SEAL TESTING OBJECTIVES

NIOSH researchers are collaborating with researchers at USACE and West Virginia University (WVU) to develop engineering procedures for the mining community to use for new seal designs [11; 12; 13]. These guidelines should aid two groups involved with the seal design process, first licensed professional engineers who develop and analyze the designs and second, regulatory officials who evaluate and approve the designs. Major efforts to date include: (1) cataloging existing 20 psi seal test data, (2) developing basic seal analysis methods, (3) developing seal foundation analysis methods, and (4) developing simple analysis tools for seal design.

USACE is engaged in modifying its Wall Analysis Code (WAC) for better application to mine seal design and analysis [14]. Key features of the new Wall Analysis Code for Mine Seals (WAC-MS) are:

- Selection of design pressure-time curves from the final rule,
- Selection of typical construction materials for mine seals,
- Structural analysis considering bending failure (wall analysis) or shear failure (plug analysis),
- Foundation analysis considering different foundation materials and depth of hitching.

WAC is a single-degree-of-freedom (SDOF) structural dynamics model that solves the equation of motion to determine the displacement-time history at mid-height of a wall. Failure occurs if this displacement exceeds a given limit. Following Slawson [15], the equation of motion for a SDOF system is

$$M \cdot y''(t) + C_d \cdot y'(t) + R\big(y(t)\big) = F\big(t\big) \qquad \text{Eq. 1}$$

where

M = equivalent or “lumped” mass of the system
C_d = damping coefficient taken as 5% of the critical value, i.e. very lightly damped
$y(t)$ = displacement of the mass as a function of time t

$y'(t)$ = velocity of the mass or first derivative of displacement
$y''(t)$ = acceleration of the mass or second derivative of displacement
R = structural resistance force as a function of displacement
F = the structural load force as a function of time, i.e. one of the design pressure-time curves developed earlier.

The critical input to WAC is the resistance function which describes the load-bearing capacity versus center-point displacement for the structure. This resistance function describes the load bearing capacity through its peak, or failure load, and continuing into the post-failure region of the structure. The resistance function contains the effects of all factors affecting the structural behavior of the seal including the strength and stiffness of both the seal structure and the seal foundation.

Resistance functions are determined for seal structures using finite element methods or other suitable numerical structural analysis tools. Each seal with its specific geometry, construction material, and foundation condition will have a unique resistance function. WAC contains families of resistance functions for different conditions. When using WAC, the program selects a resistance function to apply depending on the specifics of the problem.

The primary objective for this testing effort is to measure directly the resistance function in order to validate select resistance functions within WAC that were determined with numerical structural analysis. The testing effort must provide validation data for seal design and analysis considering four major factors that control or resist failure:

1) Construction material
2) Foundation conditions
3) Hitching conditions
4) Roof-to-floor convergence

4 DESIGN OF THE SEAL TEST FIXTURE

4.1 BASIC TEST REQUIREMENTS

In designing a method to test seals, NIOSH researchers considered the ASTM E 72-02 method for conducting strength tests of panels for building construction [16]. In this method, a 4-point bending load is applied to test panels oriented either vertically or horizontally. Minimum width for a test panel is 4 ft.

For seals designed using the 120 psi pressure-time curve with instantaneous rise time, the equivalent static pressure is 240 psi, since the dynamic load factor is 2. Assuming a test panel 4-ft-wide and 6-ft-high, loaded with a uniform pressure of 240 psi, the equivalent force is 830,000 lb. A design load of 900,000 lb was selected for designing the seal test fixture.

4.2 THE MINE ROOF SIMULATOR AT NIOSH

The Mine Roof Simulator (MRS) is a servo-controlled hydraulic press capable of applying a 3 million pound vertical load and simultaneously, a 1.6 million pound shear load. As described by Barczak [17], the MRS was custom-built in 1979 by MTS Systems Corporation for the former U.S. Bureau of Mines. In 2009, MTS rebuilt and updated the servo-control systems for NIOSH. Figure 3 shows a longwall shield in the MRS as it is being prepared for testing.

The load frame has several distinctive characteristics. The platens measure 20 ft by 20 ft. The upper platen can be moved up or down and hydraulically clamped into a fixed position on the support columns to establish the testing height. The maximum vertical opening between the upper and lower platen is 16 ft.

Controlled movement of the lower platen provides load application. The machine is a biaxial load frame, capable of applying both a vertical load and a horizontal load in one direction. All actuators are equipped with special hydrostatic slip bearings to permit simultaneous vertical and horizontal travel while under load. The capability to provide controlled loading simultaneously in two orthogonal directions is unique at this scale. Figure 4 is another view of the MRS showing the lower platen and the hydraulic actuators underneath the lower platen for vertical load application.

Figure 3 – NIOSH’s Mine Roof Simulator (MRS) [17].

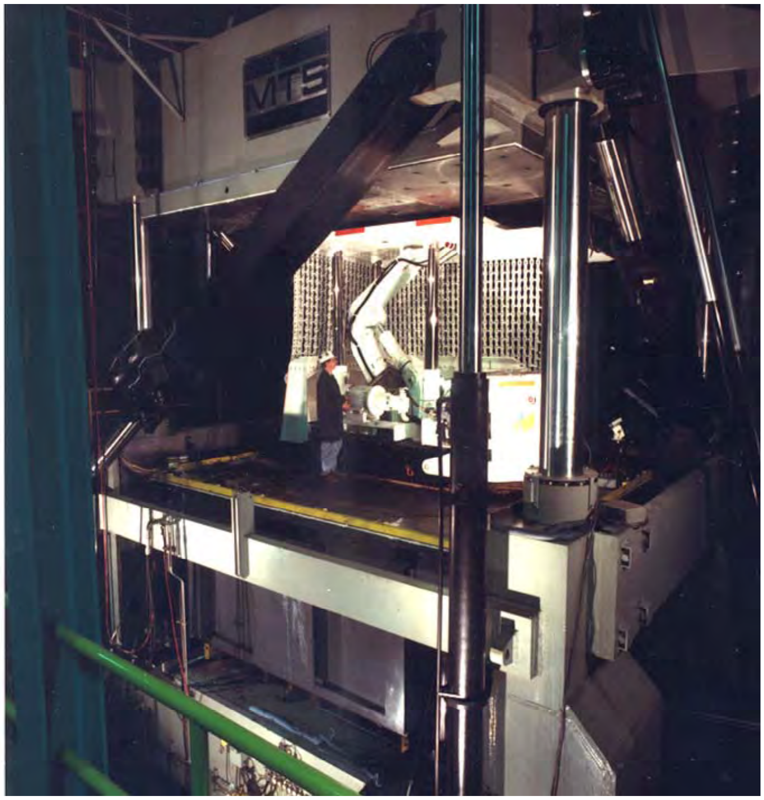

Figure 4 – NIOSH’s Mine Roof Simulator showing the lower platen. Hydraulic cylinders under the lower platen can apply a 3 million pound vertical force and a 1.6 million pound shear force.

Vertical loading is provided by a set of four actuators, one beneath each corner of the lower platen. Loads of up to 3 million pounds can be applied in the vertical direction by upward movement of the lower platen. The vertical range of motion for the lower platen is 24 in.

Horizontal loading is also provided by four actuators, with two actuators located on the sides of the lower platen just below the floor level. These actuators act in pairs and provide horizontal displacement of the lower platen in either a positive or a negative (x) direction. Maximum horizontal loading is 1.6 million pounds, and the horizontal range of motion of the lower platen in the x-direction is 16 in. There is no lateral movement capability in the y-direction of the lower platen, but this axis reacts to loads induced by the specimen.

Six degrees of freedom control of the lower platen are provided by the unstressed reference frame which provides feedback on platen displacements and rotations to the closed-loop control system. Pitch, yaw, and roll of the lower platen are controlled to keep the lower and upper platens parallel during load application. Shock absorber actuators are positioned on the left and right sides of the lower platen. These shock absorbers limit the displacement of the lower platen to less than 0.1 inch in the event of sudden failure of the support specimen.

Two hydraulic pumps provide 3,000 psi of pressure to the vertical and horizontal actuators during load application. The rate of movement of the lower platen is limited by the 140 gpm capacity of the hydraulic pumps. The maximum platen velocity assuming simultaneous vertical and horizontal displacement is 5.0 in/min.

4.3 MRS SEAL TESTING FIXTURE CONCEPT

Figures 5, 6, and 7 illustrate the basic concepts behind the MRS seal testing fixture. The main concept behind this seal testing fixture is to use the vertical loading capability of the MRS to simulate a roof-to-floor convergence load on a seal test specimen and the shear loading capability to apply load to the face of the seal test specimen.

As shown in figure 5, the seal test specimen consists of the test seal and the upper and lower foundation blocks. The test seal measures 4-ft-wide by 6-ft-high. Its thickness varies, depending on construction material, and can range from 1 to 4 ft. The foundation blocks measure 4-ft-wide by 3-ft-high by 4- to 7-ft-long. These blocks are cast concrete of varying strength and may or may not contain a notch to simulate floor hitching. Total height of the seal test specimen in the MRS is 12 ft.

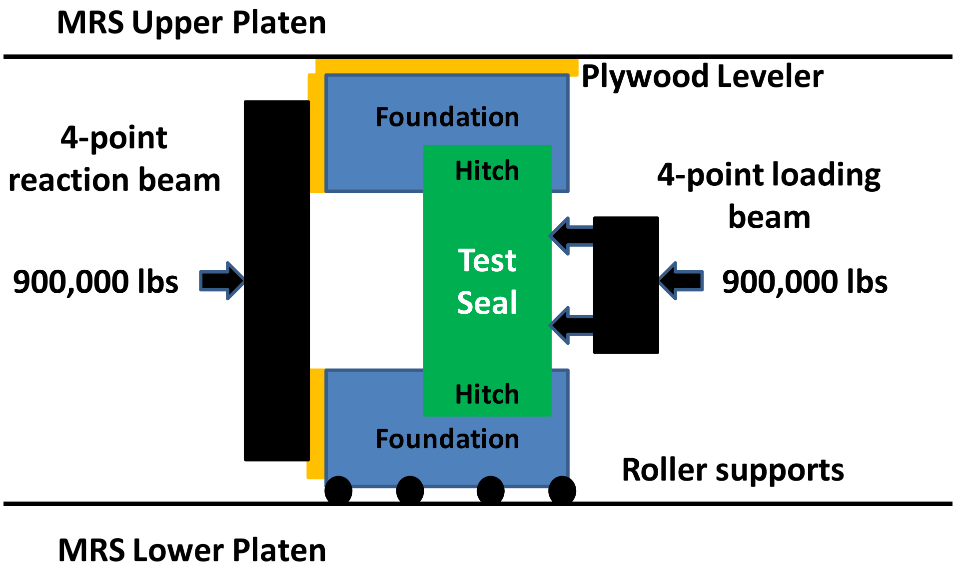

Figure 5 – Side view of Concept for MRS Seal testing Fixture (I) – Four point loading and reaction beams apply design 900,000 lb bending and shear force to the test seal and foundation. Vertical load from upper and lower platens apply simulate roof-to-floor convergence on test specimen.

Roller supports consisting of 1-in-diameter, 4-ft-long steel rods are placed under the seal test specimen on 3-in centers. These rods facilitate positioning of the seal test specimen during set-up and then ensure that the lower platen of the MRS slides under the specimen when the MRS's shear loading capability is used to apply load on the face of the seal test specimen. To compensate for surface irregularities and lack of parallelism between the upper and lower surfaces of the seal test specimen, plywood is placed between the upper specimen surface and the upper platen of the MRS. Depending on the experience with plywood, researchers may place high density rubber or a hydraulic flat-jack at this point to compensate for surface roughness and lack of parallelism.

Also shown in figure 5 are the 4-point loading and reaction beams that apply bending and shear load to the seal test specimen. The four 4-point loading beams apply equal force to the seal face at the "quarter points." These equal forces are distributed using a 6-in-high strip across the width of the test seal to avoid excessive local stress concentrations and localized punching into the test seal face. Reactive forces on the other side of the seal test specimen are collected by four 4-point reaction beams. The reaction forces are distributed equally between the upper and lower foundation blocks. These reaction forces are distributed over most of the face of the 4-ft-wide by 3-ft-high foundation block. To compensate for surface irregularities on the foundation block faces, plywood is placed between the four 4-point reaction beams and the foundation block faces. If the plywood proves inadequate, researchers may substitute high density rubber or a hydraulic flat-jack. To compensate for any lack of parallelism between the 4-point loading beams, the 4-point reaction beams and the seal test specimen faces and to assure that the applied and reaction loads are distributed equally, the 900,000 lb design load and reaction force are applied via a roller connection between the 4-point beams and the loading and reaction beams.

Figure 6 shows the two opposing triangular frames to translate the horizontal shearing force of the MRS into 4-point bending and shear load on the test seal face. The design load on the seal face of 900,000 lb is developed by the MRS's horizontal actuators beside the lower platen. This force is transferred to the horizontal loading and reaction beams via diagonal loading plates on either side of the seal test specimen. The loading and reaction beams then transfer the 900,000 lb design load to the four 4-point loading and reaction beams shown in figure 5. The support columns serve to keep the loading and reaction beams in place relative to the test seal.

Figure 7 is an artist's rendition of the MRS seal test fixture showing the test seal with the upper and lower foundation blocks, the four 4-point loading beams, the horizontal main loading beam, the support columns and the diagonal loading plates. The diagonal loading plates are welded to base shoes which in turn are bolted to the platens of the MRS. The overall MRS seal test fixture stands 12-ft-high. Note the person in the rendition for scale.

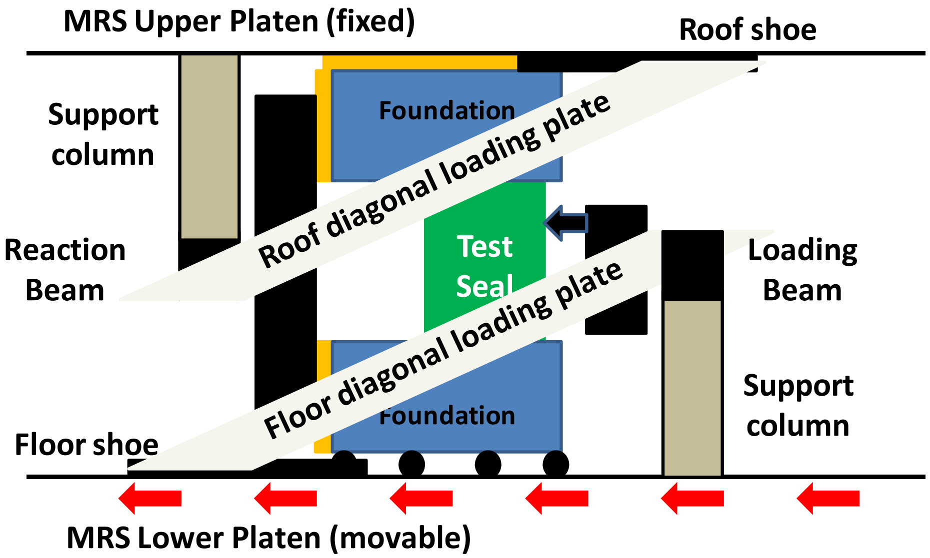

Figure 6 – Side view of Concept for MRS Seal testing Fixture (II) – Horizontal displacement of lower platen generates a 900,000 lb design load via diagonal loading plates attached to the upper and lower platens of the MRS.

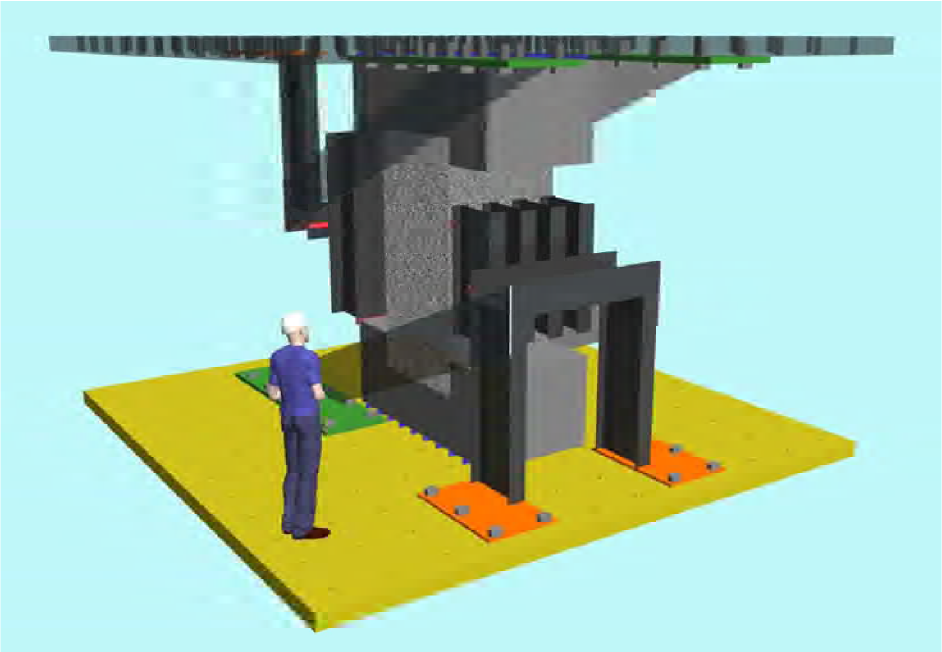

Figure 7 – Artists view of MRS seal testing fixture and a seal test specimen.

5 STATIC ANALYSIS OF MRS SEAL TEST FIXTURE

Based on the 900,000 lb maximum design load, analyses were conducted to estimate maximum loads and bending stresses in each member of the loading frame. Figure 8 shows the force resolution on each side of the test fixture. The bolts holding the base shoe to the lower platen must resist shear and tensile loads of 450,000 and 337,500 lb, respectively. The diagonal loading plate must resist a tensile load of 562,500 lb, and the support column must resist a compressive load of 337,500 lb.

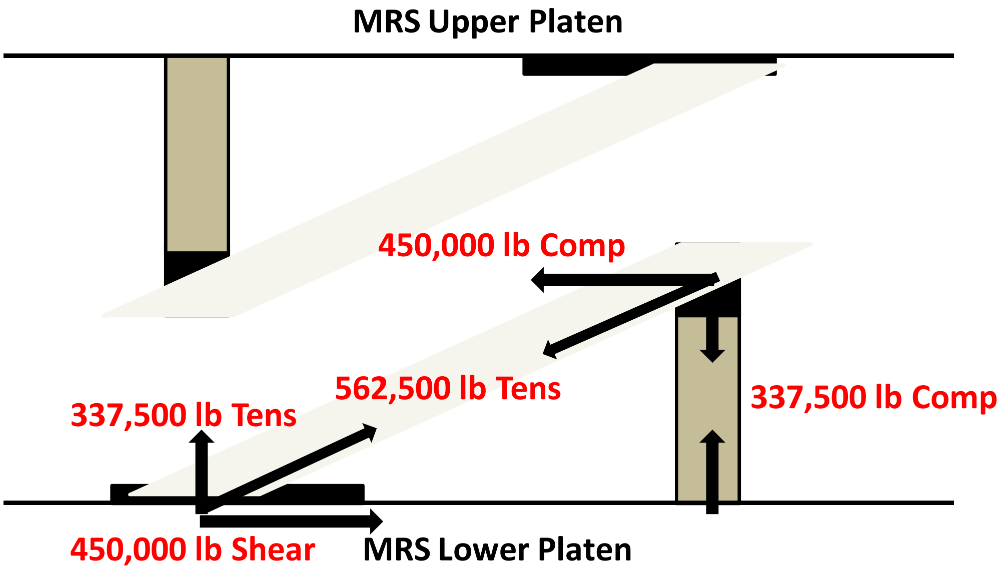

Figure 8 – Forces in MRS seal testing fixture.

The horizontal main loading beams are simply supported and have a span of 5 ft. The 900,000 lb design load is distributed over the central 4 ft of these beams. Maximum bending moment in these beams is therefore 8,100,000 in-lb. The four 4-point loading beams are simply supported, have a span of 3 ft and a load of 225,000 lb. Maximum bending moment in these beams is 2,025,000 in-lb. The four 4-point reaction beams have a span of 6 ft, and maximum bending moment in these beams is 4,050,000 in-lb.

Table 2 summarizes the maximum loads and bending moments in each member of the loading frame. Assuming yield strength of 36,000 psi for steel, the required area or section modulus is estimated for each member as:

$$A = \frac{L}{\sigma_y} \qquad \text{Eq. 2}$$

$$S = \frac{M}{\sigma_y} \qquad \text{Eq. 3}$$

where

A = required area (in^2)
L = maximum load (lb)
S = section modulus (in^3)
M = maximum bending moment (in-lb)
σ_y= yield strength (psi)

Based on the required area or section modulus, a design section was selected for each member. The approximate safety factor at maximum design load is also provided in table 2. To simplify fabrication, similar dimensions were selected for key members; hence, the size of many members is 24 in. The capacity of the MRS seal test rig is governed by the horizontal main loading and reaction beams which have the lowest safety factor of 1.15. Figure 9 shows the safety factor in each member of the MRS seal test fixture.

As a check on the above simple analysis of the MRS seal test fixture, a finite element code was used to analyze the design. Figure 10 shows the stresses in each member. Maximum stress does not exceed 32,000 psi; therefore, the test fixture should remain linear elastic everywhere. The computed safety factors reported for each member in table 2 agree with the safety factors computed using the finite element method.

Table 2 – Summary of design loads or bending moments, design sections, and safety factors for each member in the MRS seal test fixture.

Member Load	**or bending moment**	**Required area or section modulus**	**Design section**	**Actual area or section modulus**	**Safety Factor**
Diagonals (2)	562,500 lb	16 in^2	Plate 24 in x 1 in	24 in^2	1.50
Columns (2)	337,500 lb	9.4 in^2	W24x55	16.2 in^2	1.72
Loading and reaction beams	8,100,000 in-lb	225 in^3	W24x104	258 in^3	1.15
4-pt loading beams (4)	2,025,000 in-lb	57 in^3	W24x55 (4 required)	114 in^3	2.03
4-pt reaction beams (4)	4,050,000 in-lb	113 in^3	W24x104 (4 required)	258 in^3	2.29

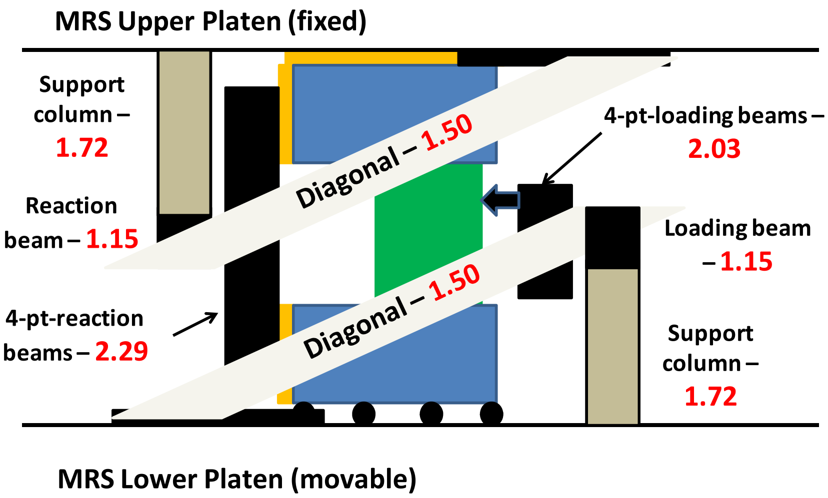

Figure 9 – Summary of safety factors in design of MRS seal test fixture.

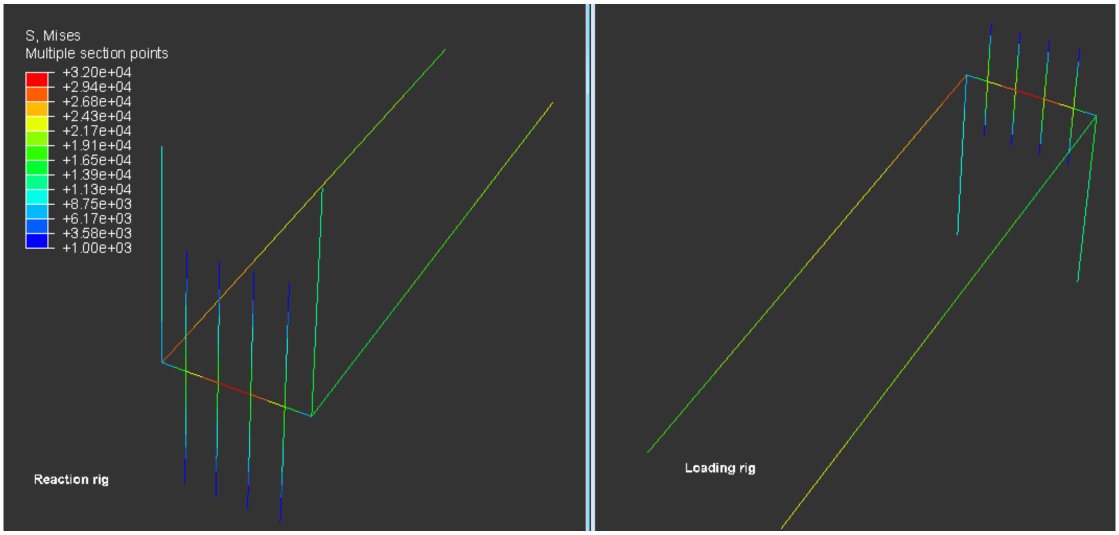

Figure 10 – Finite element analysis of stresses in the MRS seal test fixture.

6 MRS SEAL TESTING PROGRAM

As mentioned in the objectives, the seal testing effort must provide validation data for seal design and analysis considering construction material, the seal foundation, hitching, and roof-to-floor convergence. Table 3 summarizes the four factors in this program. Four different construction materials are considered – reinforced concrete, plain concrete, cementitious foam, and polyurethane foam with aggregate. These four materials cover all of the approved seals in existence at this time. The program will address two extreme foundation conditions, weak and strong. To simulate weak foundation conditions in a coal mine, the foundation block is cast from a 500 psi concrete; whereas, the strong foundation conditions use a 5,000 psi concrete. This range covers most practical coal mining foundation conditions. The program also examines hitching and will simulate the extremes, either no hitch or a 1-ft-deep hitch. Again, this range of hitch depth covers most practical conditions. Finally, the program will examine the effect of roof-to-floor convergence on seal performance. Tests will have either zero roof-to-floor convergence applied prior to loading the seal face, or they will have convergence applied that is similar to that in approved seal designs. The total number of planned tests is 32 (4 x 2 x 2 x 2). Each test will be conducted in the MRS using both vertical and horizontal displacement control.

As mentioned earlier, a central objective for these tests is to measure resistance functions for seal structures directly in order to validate the resistance functions incorporated into WAC-MS for mine seal analysis. These tests will also provide validation data for other methods used for structural analysis and design of mine seals. The resistance functions incorporate all the factors affecting structural response of a seal including the seal structure itself plus the foundation and hitch for the seal. The resistance functions also include all the expected failure modes for the seal. This seal test program will examine three seal failure modes that depend on the relative strengths of the seal structure, the foundation, and the hitch. Figure 11 shows the four expected failure modes through the seal test specimen, which are bending or tensile failure through the seal structure, shear failure through the foundation, shear failure along the seal-foundation interface, or shear failure through the seal. Table 3 indicates the expected failure mode for each of the 32 tests in the seal test program matrix. The intent is to obtain multiple failures in each mode.

The MRS has a data acquisition system capable of recording 48 data channels. The actuator pressures of the MRS provide a direct measure of vertical and horizontal loads on the seal test specimen. Because these loads are a substantial fraction of the capacity of the MRS, there is no need to incorporate a load cell within the seal test fixture. String potentiometers will record displacement of the seal face during the test. Strain in the MRS test fixture will be recorded at numerous points to confirm that the fixture is applying uniform loads on the seal test specimen as planned. Strain monitoring points include:

- Several points along the diagonal loading plates,
- Several points along the main loading and reaction beams,
- The midpoint of the four 4-point loading and reaction beams.

Table 3 – MRS seal test program matrix and the expected failure mode.

Foundation	**Hitch**	**Roof-to-floor convergence**	**Construction material**			
			Reinforced concrete	**Plain concrete**	**Cementitious foam**	**Polyurethane foam and aggregate**
Weak	None	None	Interface or seal	Interface or seal	Interface or seal	Interface or seal
Weak	None	Yes	Interface ,seal or foundation	Interface or seal	Interface or seal	Interface or seal
Weak	1 ft	None	Foundation or seal	Foundation or seal	Foundation or seal	Foundation or seal
Weak	1 ft	Yes	Foundation or seal	Foundation or seal	Foundation or seal	Foundation or seal
Strong	None	None	Seal or interface	Seal or interface	Seal or interface	Seal or interface
Strong	None	Yes	Seal or interface	Seal or interface	Seal or interface	Seal or interface
Strong	1 ft	None	Seal or foundation	Seal or foundation	Seal or foundation	Seal or foundation
Strong	1 ft	Yes	Seal or foundation	Seal or foundation	Seal or foundation	Seal or foundation

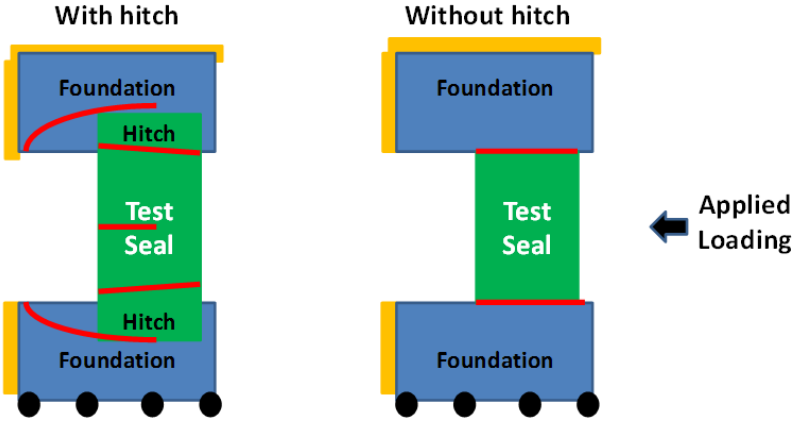

Figure 11 – Expected failure modes through seal test specimen – 1) bending or tensile failure through the seal structure (left), 2) shear failure through the foundation (left), 3) shear failure along the seal-foundation interface (right), or 4) shear failure through the seal (left).

The MRS seal test fixture only delivers a static equivalent load to the seal test specimen. Unfortunately, the current explosion test capabilities at the Lake Lynn Experimental Mine are not available in the near future. One avenue to test mine seal structures under dynamic conditions is with the Blast Load Simulator (BLS) owned by USACE. The BLS, shown in figure 12, applies a near uniform blast wave across the test seal face. The dynamic driver of the BLS is a cold gas pressurized chamber. The gas is air or helium at a static pressure of 1500 psi. The pressure chamber can be enlarged to increase pressure duration time. The pressurized gas is released with a rupture disk diaphragm. The BLS can test mine seals up to 4 ft wide, 6 ft height and 1 ft thick. Figure 13 shows the target inside of the BLS, which in this case is a concrete block wall, and Figure 14 shows the aftermath of the test. With the BLS, it is possible to conduct dynamic tests on mine seals considering various construction materials, foundation conditions, and hitching using a repeatable, uniform blast wave.

Figure 12 – Overview of Blast Load Simulator (BLS) at U.S. Army Corps of Engineers.

Figure 13 – Test wall inside Blast Load Simulator

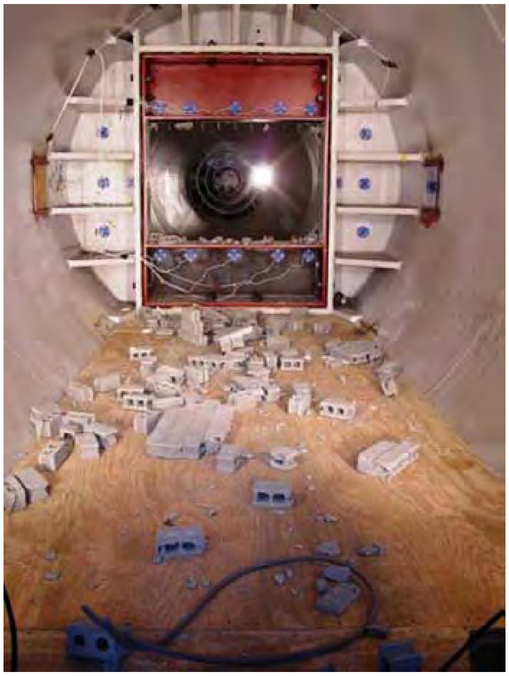

Figure 14 – Aftermath of test on concrete block wall in BLS.

7 SUMMARY

The final rule for mine seals increased their design strength from 20 psi to 240 psi static-equivalent pressure and specified new requirements for their engineering and construction. Prior to the enactment of the new mine seal regulations, testing at NIOSH’s Lake Lynn Experimental Mine examined the resistance of seals to explosion loads subject to the old 20 psi seal design standard. Prior testing did not consider the effects of seal foundation conditions or roof-to-floor convergence on seal design and performance. NIOSH researchers identified the following factors that require consideration in a new seal testing effort to validate seal analysis and design methods:

1) Seal construction material
2) Foundation conditions
3) Hitching conditions
4) Roof-to-floor convergence

NIOSH researchers designed and analyzed a new seal test fixture for use in the MRS. The fixture uses the vertical loading capability of the MRS to simulate roof-to-floor convergence and its shear loading capability to apply load to the face of the test seal. The fixture also includes foundation blocks to simulate different foundation and hitching conditions. With this fixture, researchers can examine the above factors that affect seal performance and observe a range of expected failure modes. These tests will provide direct measurement of resistance functions to validate WAC-MS presently under development by USACE.

The MRS seal test fixture only delivers a static equivalent load to the seal test specimen. To test mine seal structures under dynamic conditions, the Blast Load Simulator (BLS) can be used. With the BLS, it is possible to conduct dynamic tests on mine seal models considering various construction materials, foundation conditions, and hitching using a repeatable, uniform blast wave.

The MRS seal test fixture is under construction and should be operational by May 2010. Test results are expected during 2010. The test program will examine the range of approved seal designs considering construction material, foundation conditions, floor hitching, and the effect of roof-to-floor convergence. The new regulation requires seal designers to consider these factors to receive approval for a new seal design. The seal test program described herein should provide data to validate structural analysis and design methods used during seal engineering.

DISCLAIMERS

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