Report on Miner Refuge Chamber Displacement Analysis
Raytheon UTD
11 December 2007

Contract Number: 254-2008-M-23921
Task 4: Deliverable Item for Subtasks 1 and 2

Objectives:

Task 4 examines the effect of a methane explosion on the dynamics of three miner's refuge chambers. This will help provide an initial understanding of the robustness of these chambers under possible mine emergency conditions. Specifically, the objectives for Sub Tasks 1 and 2 of Task 4 are as follows:

1. Determine the magnitude and type of possible motion for all three structures as a function of linear distance from the explosion.
2. Determine the anchorage forces required to limit or prohibit any motions determined in #1 above for all three structures.

Executive Summary:

Given the pressure profile of a methane explosion at various distances from where it was ignited and the analysis performed using the accompanying "TD28ST3- Miner Refuge Chamber Displacement Analysis.xls" simulation tool developed to address the above objectives, it can be shown that all three of the refuge chambers (ChemBio/AL Lee 4042-20, Strata Products MC36, and Kennedy MPLC-H12_8155-C) in the study will undergo a form of displacement from its initial position in the tunnel.

The cross-sectional area has a direct correlation on the type of motion predicted. The ChemBio/AL Lee 4042-20 and Strata Products MC36 have almost equivalent pre-inflated cross-sectional areas. As a result, both exhibited only translational displacement away from the blast. The smallest profile chamber, the Strata Products MC36, had a translational displacement of 2.9 to 9.6 feet, while the ChemBio/AL Lee 4042-20 translated 5.4 to 14.3 feet across the range of initial positions examined.

The Kennedy MPLC-H12_8155-C chamber, with the largest cross-sectional area, exhibited both translational and rotational displacement. This cross-sectional area helped to produce the largest calculated translation among the group with 8.3 to 24.8 feet of displacement. The force of the methane explosion would be large enough to cause the chamber to hit the 7-foot high roof of the D-Drift as it underwent rotational displacement. This behavior was consistent across the range of initial D-Drift positions that were examined.

The Excel spreadsheet simulation tool produced from the Task 4 effort also calculates the forces required to keep each chamber from moving and can be used to help evaluate possible solutions for preventing or minimizing the motion of a refuge chamber being acted upon by the force of a methane explosion in a mine entry or tunnel.

Assumptions:

1. The Pressure vs. Time curves for the methane explosion at various distances away from the ignition point, as provided by M. Kaminskas of Raytheon UTD, are an accurate representation of the explosion data from Lake Lynn Experimental Mine simulation tests #464D. Location D4 exhibits the largest pressure among the locations measured during the LLEM tests. This is not immediately intuitive as blast pressure would seem to decrease with increasing distance from the ignition point. A further understanding of this phenomenon may be needed, but is beyond the scope of this effort.
2. The coefficients of friction were defined to be between steel (the chamber material) and shale floor covered in rock dust (crushed limestone to a depth of 2 or 3 inches):
    a. Static Friction coefficient = 1; conservative estimate
    b. Minimum Kinetic coefficient of friction = 0.4, provided by G. Finfinger 11/26/2007
    c. Maximum Kinetic coefficient of friction = 0.7, provided by G. Finfinger 11/26/2007
3. Each chamber's center of gravity is located at its centroid.
4. The methane explosion force acts as a point load acting at the middle of the end face of the chamber parallel to the axis of the tunnel.
5. The width of the chamber is centered in the width of the tunnel. [Prior analysis by M. Kaminskas indicated negligible difference in explosion pressure behavior compared to the chamber being located closer to one rib of the tunnel.]
6. If rotational displacement occurs, the methane blast will continue to act as a point load (in the direction parallel to the axis of the tunnel) acting in the center of the end face of the box.
7. The chamber acts as a rigid body that does not deform under the applied forces.
8. The explosion's pressure curve will maintain its shape throughout displacement of the chamber. As the Pressure vs. Time curves at various distances away from the ignition point indicates, the maximum pressure is a function of distance from the ignition point. Hence, as the chamber displaces, the pressure profile acting on the chamber should also change. Since, this requires a higher level of analysis, this will be assumed "constant" to for the purposes of this "first order" effort.

Procedure:

The following section describes the development of the simulation tool and the equations used for predicting motion of the chamber. The refuge chamber was considered to be a rigid body. Hence the free body diagram (Figure 1) and equations for rigid body motion were used for this simulation tool. These equations were then put into a spreadsheet to provide an efficient means of sequentially analyzing and comparing a variety of cases.

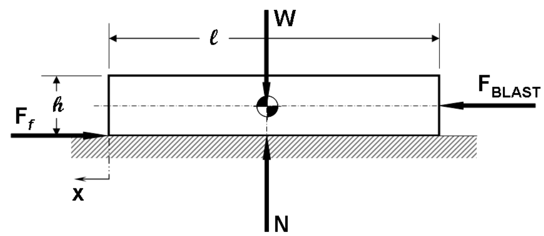

Figure 1: Free Body Diagram of Chamber

Translational Component of the Chamber Displacement:

In order for the refuge chamber to translate, the force of the methane explosion must exceed the force of **static** friction F_f between the chamber and the mine floor:

$$F_{BLAST} > \mu_s W$$

If $F_{BLAST} > \mu_s W$, then Newton's 2nd Law and the equation for **kinetic** friction can be used to determine the acceleration a of the chamber as shown below:

$$F = \frac{W}{g} a = F_{BLAST} - \mu_k W$$

In order to determine the translation displacement of the chamber, the explosion's pressure curve, as shown in Figure 2, will have to be examined.

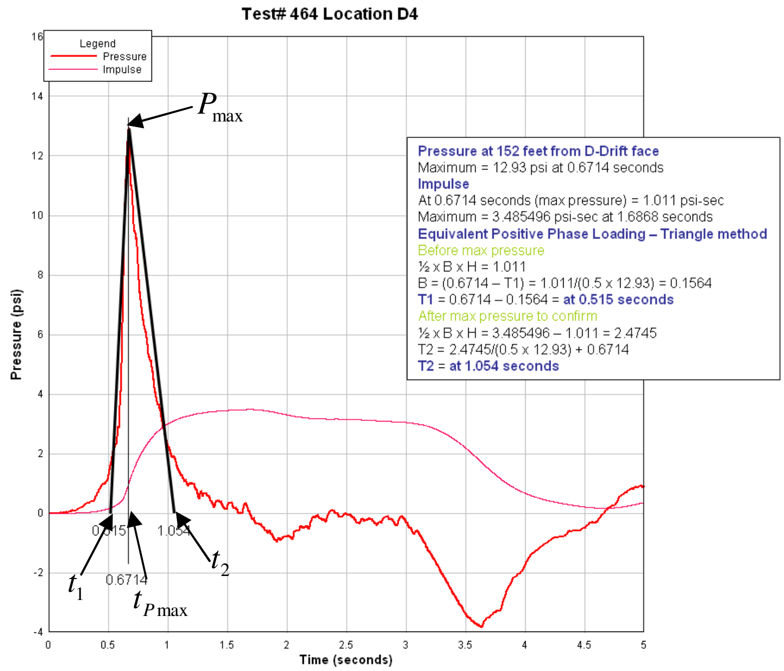

Figure 2: Methane Explosion Pressure Curve

As the plot shows, the pressure linearly increases from $t_1 \le t \le t_{P\max}$. During this time period, the applied pressure can be described by the following equation since rigid body motion is being assumed and the cross-sectional area is a constant:

$$P(t) = \frac{P_{\max}}{t_{P\max} - t_1} t$$

Consequently, acceleration linearly increases with time during $t_1 \le t \le t_{P\max}$. The force of the explosion is determined by the product of the chamber's cross-sectional area and the pressure curve, or $F_{BLAST}(t) = P(t) \times h \times w$. Newton's 2nd Law can then be solved for a_1 as shown below:

$$a_1(t) = \left(\frac{P_{\max} hwg}{W(t_{P\max} - t_1)} \right) t - \mu_k g$$

The velocity and displacement of the chamber can then be determined as shown below

$$v_1(t) = \int_{t_1}^{t_{P\max}} a_1(t)dt = \frac{P_{\max} hwg}{2W} (t_{P\max} - t_1)^2 - \mu_k g(t_{P\max} - t_1)$$

$$\Delta x_1(t) = \int_{t_1}^{t_{P\max}} v_1(t)dt = \frac{P_{\max} hwg}{6W} (t_{P\max} - t_1)^3 - \frac{\mu_k g}{2} (t_{P\max} - t_1)^2$$

Similarly, the chamber velocity and displacement can be determined for $t_{P\max} \le t \le t_2$ as shown by the following equations:

$$v_2(t) = \frac{-P_{\max} hwg}{2W}\left(t_2 - t_{P\max}\right)^2 + \mu_k g\left(t_2 - t_{P\max}\right)$$

$$\Delta x_2(t) = \frac{-P_{\max} hwg}{6W}\left(t_2 - t_{P\max}\right)^3 + \frac{\mu_k g}{2}\left(t_2 - t_{P\max}\right)^2 + v_1 t$$

For $t_2 < t$ only the force of kinetic friction is acting on the chamber in the direction along the axis of the tunnel. Consequently, Newton's 2nd Law can be rearranged to provide the chamber acceleration $a_3 = \mu_k g$ Because the chamber is under constant acceleration at this time, the kinematics equation below can be used:

$$\Delta x_3(t) = \tfrac{1}{2} a_3\left(t - t_2\right)^2$$

$$v_3(t) = v_2 + a_3\left(t - t_2\right)$$

The chamber displacement then becomes:

$$\Delta x_3(t) = \tfrac{1}{2}\mu_k g\left(\frac{-v_2}{\mu_k g}\right)^2$$

The total displacement of the chamber x_T becomes:

$$\Delta x_T = \Delta x_1 + \Delta x_2 + \Delta x_3$$

Force to Prevent Chamber Rotation

To determine the restraining force required to prevent the translation of the chamber, the free body diagram is examined again with the restraining force added as shown in Figure 2:

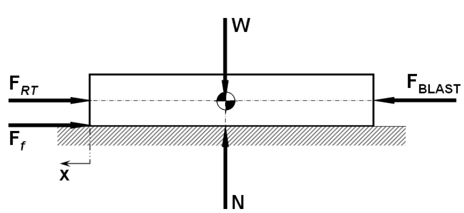

Figure 2: Translational restraining force on chamber

Summing the forces in this **static** free body diagram yields a reaction force F_{RT} to prevent the refuge chamber from translating:

$$F_{RT} = F_{BLAST} - \mu_s W$$

Rotational Component of the Chamber Displacement:

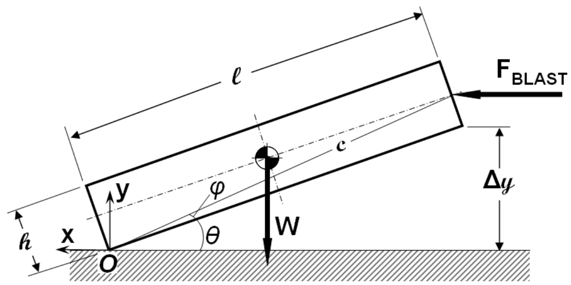

Figure 3: Chamber undergoing rotational displacement

In order for the refuge chamber to rotate, the moment M_{BLAST} caused by the methane explosion must exceed the moment M_W due to the weight of the chamber:

$$M_{BLAST} > M_W$$

or

$$F_{BLAST}(c \cdot \sin\varphi) > W\left(\tfrac{1}{2}c \cdot \cos\varphi\right)$$

where $c^2 = (l)^2 + \left(\frac{h}{2}\right)^2$ and $\varphi = \tan^{-1}\left(\frac{(h/2)}{l}\right)$.

If $M_{BLAST} > M_W$, then the chamber will rotate and conservation of energy can be used to determine the amount of rotation. This **assumes there will be no obstruction (i.e. tunnel roof) impeding the rotational motion of the chamber**. That is, the kinetic energy KE of the chamber at maximum rotational velocity must equal the potential energy PE of the chamber at its maximum height or:

$$KE = PE$$

or

$$\tfrac{1}{2} J_{MO}\omega_{max}^2 = Wy_{max}$$

$$\tfrac{1}{2} J_{MO}\left(\frac{2v}{c}\right)^2 = \frac{Wc}{2}\sin(\theta+\varphi)$$

where J_{MO} is the Moment of Inertia of the chamber relative to the axis of rotation at O and is calculated as follows:

$$J_{MO} = J_M + \left(\tfrac{1}{2}c\right)^2\left(\frac{W}{g}\right)$$

Using J_M , the Moment of Inertia about the center of the chamber…

$$J_M = \frac{W}{g}\left[\frac{\left(\tfrac{1}{2}c\right)^2}{3} + \frac{h^2}{12}\right]$$

… J_{MO} can be calculated as shown below:

$$J_{MO} = \frac{W}{g}\left[\frac{c^2}{3} + \frac{h^2}{12}\right]$$

The velocity v can be determined by examining the Centrifugal Force created by the rotating chamber:

$$F_c = \frac{(W/g)v^2}{\frac{1}{2}c} = F_{BLAST}\cos(\theta+\varphi) + W\sin(\theta+\varphi)$$

Solving for v…

$$v = \sqrt{\frac{gc}{2W}\left[F_{BLAST}\cos(\theta+\varphi) + W\sin(\theta+\varphi)\right]}$$

The Conservation of Energy equation can be rearranged to solve for the chamber's angle of rotation θ:

$$\theta = \sin^{-1}\left(\sqrt{\frac{1}{(W/F_{BLAST})(Wc^2/2J_{MO}g - 1) + 1}}\right) - \varphi$$

The height the chamber rotates can be defined as:

$$\Delta y = c\sin(\theta+\varphi)$$

In the case where the chamber rotates enough to where the top of the chamber hits the ceiling of the tunnel θ becomes:

$$\theta_{c\max} = \sin^{-1}\left(\frac{h_{tunnel}}{\sqrt{l^2+h^2}}\right) - \tan^{-1}\left(\frac{h}{l}\right)$$

where h_{tunnel} is the height of the tunnel. Consequently, the displacement of the chamber due to rotation becomes:

$$\Delta y_{c\max} = l\sin\theta_{c\max}$$

The max displacement of the center of gravity due to $\theta_{c\max}$ then becomes:

$$\Delta y_{CGc\max} = \frac{l}{2}\sin\theta_{c\max} - \frac{h}{2\cos\theta_{c\max}}$$

To determine the force of the chamber after rebounding from the ceiling and impacting the ground, Conservation of Linear Momentum is considered. As the chamber rebounds from the tunnel ceiling, Conservation of Linear Moment will cause the chamber to leave the ceiling at a velocity v_{CG2} that is equal to the incident velocity v_{CG1} of the chamber as it hits the tunnel ceiling.

$$v_{CG1} = \left(\sqrt{\frac{2W\Delta y_{c\max}}{J_{MO}}}\right)\left(\frac{\sqrt{(l/2)^2 + (h/2)^2}}{2}\right) = v_{CG2}$$

Consequently, the vertical velocity of the center of mass $v_{CG,y}$ after rebounding from the ceiling will include vertical component of v_{CG2} as well as the component due to the center of gravity falling from $\Delta y_{c\max}$.

$$v_{CG,y} = v_{CG2}\cos\theta_{cmaz} + \sqrt{2g\Delta y_{c\max}}$$

Using kinematics equations, the acceleration of the center of gravity is:

$$a_{CG} = \frac{v_{CG,y}^2}{2(\Delta y_{CGc\max})}$$

The impact force of the chamber on the ground is the defined using Newton's 2nd Law as follows:

$$F_{impact} = \frac{W}{g}a_{CG}$$

Force to Prevent Chamber Rotation

In order to determine the force needed to prevent rotation of the refuge chamber, the free body diagram as shown in Figure 4 is used.

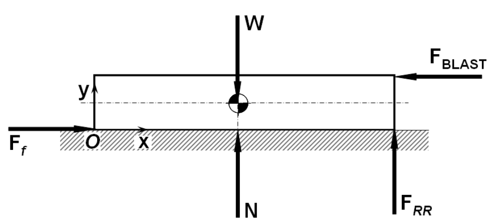

Figure 4: Rotational restraining force on chamber

Summing the moments in this **static** free body diagram yields a reaction force F_{RR} to prevent the refuge chamber from translating:

$$F_{RR} = F_{BLAST}\frac{h}{l}$$

The total motion of the refuge chamber can thus be represented as the sum of the translational displacement and the rotational displacement.

Results Discussion:

The analysis performed on the ChemBio/AL Lee 4042-20, Strata Products MC36, and Kennedy MPLC-H12_8155-C refuge chambers predicted the type of motion and approximated the amount of displacement of these chambers when acted upon by the force of a test methane explosion in the D-Drift of the Lake Lynn Experimental Mine (explosion # 464D).

The simulation that was developed for this analysis was based on fundamental equations of rigid body motion. These equations were put into a spreadsheet to provide a tool for easily comparing various parameters such as the distance of the chamber from the ignition of the explosion, or the size/weight of the various chambers on their response to the force of the explosion.

The following sections will summarize the results of the analysis for Objective 1.

Task 4 Summary:

At all locations in the D-Drift where the pressure profile was provided, all three refuge chambers should be displaced from their initial positions due to the force of the methane explosion.

Vendor	Model No.	Initial Chamber distance from Explosion at D-Drift face		Total Displacement of Refuge Chamber (Translation + Rotation)	
		Ref	(ft)	Translation (ft)	Rotation (degrees)
ChemBio/AL Lee	4042-20	D1	31	7.6 to 11.1	0.0
		D2	50	8.0 to 11.7	0.0
		D3	100	8.9 to 12.8	0.0
		D4	152	9.9 to 14.3	0.0
		D5	201	9.1 to 13.2	0.0
		D6	300	8.3 to 12.1	0.0
		D7	390	7.4 to 10.9	0.0
		D8	501	8.4 to 12.1	0.0
		D9	601	7.0 to 10.3	0.0
		D10	750	5.4 to 8.1	0.0
Strata Products	MC36	D1	31	3.9 to 7.4	0.0
		D2	50	4.2 to 7.9	0.0
		D3	100	4.7 to 8.7	0.0
		D4	152	5.4 to 9.6	0.0
		D5	201	4.9 to 8.9	0.0
		D6	300	4.4 to 8.2	0.0
		D7	390	3.9 to 7.3	0.0
		D8	501	4.4 to 8.2	0.0
		D9	601	3.6 to 6.9	0.0
		D10	750	2.6 to 5.4	0.0
Kennedy	MPLC-H12_8155-C	D1	31	11.4 to 19.3	5.1
		D2	50	12.1 to 20.4	5.1
		D3	100	13.3 to 22.3	5.1
		D4	152	14.9 to 24.8	5.1
		D5	201	13.7 to 22.9	5.1
		D6	300	12.6 to 21.1	5.1
		D7	390	11.2 to 18.9	5.1
		D8	501	12.6 to 21.1	5.1
		D9	601	10.6 to 18.0	5.1
		D10	750	8.3 to 14.2	5.1

Table 1: Displacement of Refuge Chamber due to Methane Explosion

As shown in Table 1, the ChemBio/AL Lee 4042-20 and the Strata Products MC36 chambers showed only translational displacement only. Since both chambers have a similar pre-inflated cross-sectional area and weight, the moment produced by the methane explosion is not enough to overcome the moment due to the chamber weight at the center of gravity. Hence, rotational displacement did not result for these chambers. To determine an appropriate location of where to place the pre-inflated chamber in the tunnel, the inflated dimensions of the chamber will have to be considered in addition to the chamber's displacement due to methane explosion to ensure the full volume of the inflated chamber can be used.

The largest and heaviest chamber, the Kennedy MPLC-H12_8155-C, exhibited a combined translational and rotational displacement in reaction to the explosion. This occurred at all locations at the various distances that were measured away from source of the explosion. The larger cross-sectional area as compared to the other chambers was enough to produce a moment due to the explosion force to overcome the moment due to the weight of the chamber. Consequently, the chamber is forced to rotate about its lowest edge located away from the end receiving the initial explosion impact. This rotational motion would cause the chamber to hit the tunnel roof at a height of 7 feet..

The "TD28ST3- Miner Refuge Chamber Displacement Analysis.xls" Excel spreadsheet simulation tool can be used to analyze and develop solutions for preventing or minimizing the motion of a refuge chamber. The tool calculates the force needed to prevent the translation/rotation of a chamber. This calculation can aid in the design of chamber restraining mechanisms. The spreadsheet tool can also evaluate the coefficient of friction necessary to minimize displacement of a chamber which could suggest possible modifications to the chamber lower surface texture or construction to achieve that coefficient.

Future studies:

As the pressure data indicates, the explosion pressure begins to increase as the distance increases away from the ignition point of the explosion. A peak pressure is reached at 152 feet from the explosion then decreases as the distance increases from this point. This phenomenon may require further study to determine if this could have an affect on the displacement of the chamber.

In addition, the impact of the Kennedy chamber on the tunnel roof would possibly need to be investigated to determine its effect on the structural integrity of the chamber. Likewise, the effect of the impact of this chamber as it hits the ground may also need to be studied.