5. Potential Blast Loadings for Refuge Station Bulkhead Design

5.1 Literature Review

The following table lists literature reviewed and key findings used in the preparation of this section.

Table 1. Literature and Key Findings Related to Blast Loading for Refuge Stations

Reference	Key Findings
Information Circular 9500, *"Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines,"* Zipf et. al. [1]	• Illustration of parameters contributing to the worst case severity of methane explosions. • Analytical and practical comparisons for methane only explosions in open crosscut tunnels. • Provides pressure-time results including a methane explosion with peak pressures of 15 psi. • Ignition points at the face. • Pulse duration data.
"Experimental Coal-Dust and Gas Explosions," Nagy and Mitchell [3]	• Point of origin studies. • Provides experimental data. • Description of decrease in explosion max. pressure with distance from face. • Data shows flame length = 5 x explosion length. • Pulse duration data.
Foster-Miller, Inc., Report Excerpt, *"Appendix A – Explosive Environment Definition,"* Maser et. al. [4]	• Describes physical characteristics of a methane-air explosion. • Describes attenuation of pressure by induced by blast wave passing open crosscuts. • Pressure reduced by a factor of .8 for each open crosscut passed.

Reference	**Key Findings**
Report of Investigations 7581, *"Explosion-Proof Bulkheads – Present Practices,"* D.W. Mitchell [5]	<u>Peak pressure vs. distance:</u> General statement (p. 2): Seldom do explosion pressures **200** feet and more from the origin exceed 20 psig unless coal dust is excessive. <u>Bulkhead or Seal Strengths:</u> 8" thick mortared concrete block wall (recessed around perim) stands **5** psig "at best". German thick gypsum bulkheads stand 215 psig; fail at 260 psig. Dynamic strength > static strength: Wall designed for 27 psig static survived explosions as large as 50 psig peak. Description of German air-tightness measurement/monitoring practices. <u>Leakage into Sealed Areas</u> Cracks and fissures can cause leakage even if seals are airtight. Flows not predictable, may be many hours after change in pressures (baro, etc.)
"Explosion Evaluation of Mine Ventilation Stoppings," E.S. Weiss et. al. [6]	• Charts for survival and failure pressures for various stopping materials and constructions. • Provides pressure-time data from experiments. • Pulse duration data.
"Experimental Mine and Laboratory Dust Explosion Research at NIOSH," M.J. Sapko et. al. [7]	• Experimental data of explosion pressure decrease effects with distance in drift with first four crosscuts sealed. • Example of blast signature and decay. • Pulse duration data.

Reference	**Key Findings**
"Explosion Hazard in Mining," J. Nagy [8]	This re-summarizes much data obtained by Mitchell and Nagy in 1963, plus some new information. We include only areas regarding methane-only explosions. Location of Ignition point within gas zone (p. 52): 40-ft long ideal gas ignited. At face: 39 psig. At center (20 ft outby): 27 psig At outby end (40 ft): 1 psi *Similar conclusions to Mitchell [3], 1963, co authored by Nagy*. Max Explosion Pressure vs. % Methane (Graph, p.53): Performed in a closed vessel; therefore pressures much higher than in mine. However, same relative dropoff when moving away from ideal 10% methane mixture as in Mitchell 1963 (Ref #3): 8% methane: 80 psig 10% methane: 92 (max) 12% methane: 80 *Reflects 1963 Mitchell report only w/containment vessel*. Decrease of Peak Pressure with Outby Distance: Note: as in Mitchell 1963 (Ref #3), could not find a description of the drift/passage configuration, so # of crosscuts, sealed vs. open, etc. not specifically known. For 40-ft long ideal gas ignited. Outby distance zero (at face): 39 psig " 200 ft: 23 psig " 500 ft: 13 psig *Looks same as 1963 Mitchell report data*. pp. 52-55 – graphs. Methane percentage. Tests with a 40 foot long gas zone. Explosion pressures at 0, 200, 500 ft. 39, 23, **13** psi. Where was testing? What was mine configuration? #3. Mitchell report 1963. p. 20 – ignition points. P. 24 – graphs. P. 25 – knockdown double check methane only. Pulse duration data.

Reference	Key Findings
"Explosion Considerations in Refuge Chamber Design," Presentation by Zipf and Cashdollar [9] "*Explosions and Refuge Chambers,*" Zipf and Cashdollar. Accompanying notes to presentation. [10]	• Notes from internal NIOSH presentation on latest opinions for explosion pressures on refuge chambers. • Recommendations for anchorage for stations. • Recommendations for possible chamber locations and strength. • Discussion of blast debris behavior. • Discussion of blast wind speeds. Overpressure effects on human body.
Summary of MSHA Test Data Sent to Foster-Miller on November 16, 2007 by K.L. Cashdollar.[11]	• Data from NIOSH not previously published showing (including raw data) graphs, images, and raw data of explosion tests at Lake Lynn. • In this test double open crosscuts had a bigger knockdown than the FMI model predictions. Pulse duration data.
"Experimental Study of the Effect of LLEM Explosions on Various Seals and Other Structures and Objects," K.L. Cashdollar et. al. [12]	• Explosion tests at NIOSH Lake Lynn performed for MSHA and W. Virginia Office of Miner's Health Safety and Training in support of their investigations into the Sago Mine explosion. • Information on sensor type and placement at Lake Lynn. • Definition of static from dynamic behavior. • Impact of reflected pressures seen due to a contained explosion with main drift and crosscut entries blocked. This was a 71 ft gas zone (ignition zone). • Shows flame lengths. • Typical seal construction time illustrated for a Mitchell-Barrett seal. Pulse duration data.
"Assessment of Refuge Bay Designs in Collieries," J.W. Oberholzer	<u>Suction loads on walls:</u> Determined to be on order of 1 psig. Cites Nagy 1981 [8] saying that "provision should be made for **5** psi".

5.2 Characterization of Blast Events

A fundamental driver for the design of any in-mine refuge station is the need to survive the blast loadings that can occur in the locations planned for deployment. Much valuable research and testing has been conducted, particularly by MSHA/NIOSH at the Lake Lynn mine test facility (LLEM), in which many blast conditions have been replicated, measured, and data published. For the purposes of developing rational and reasonable design criteria for the design of bulkhead-type refuge stations, much of this work along with that of other researchers has been carefully reviewed. This has resulted in development of a basic two-level approach:

- A transient "design" pressure pulse can be developed that would envelop nearly all of those conditions which are most likely to occur, given an understanding of conservative assumptions for the many parameters that affect the magnitude and duration of such a design pulse. The bulkhead system would need to survive this with no significant damage or compromise of operation post-blast; and

- Understanding of the rare but more severe conditions that could conceivably occur with ideal combinations of circumstances, and use those conditions as an ultimate loading criterion in which damage might occur but short of the destructive level. This would provide some measure of reserve without penalizing designs for very unlikely conditions. This is explained more fully in the following chapter dealing with the design and performance of the proposed bulkhead-type refuge stations.

To accomplish this, a good characterization of blast events is needed, including understanding of how the important blast variables affect the blast loadings on such stations. In this report, we base this on methane-only explosions, since in modern mines proper rockdusting control and other measures are designed to eliminate coal dust explosions. This not only is needed for development of appropriate refuge station loadings, but also can serve to guide the management and placement of these stations to provide the maximum level of safety with economy of operations.

These variables can be grouped into the following categories:

- The exploding body of gas itself, including methane concentration, combustible gas volume, and ignition point relative to any closed or working faces. This determines the initial blast energy and nature of the blast and flame fronts that quickly move outward into the mine (see Section 5.3).

- The configuration of the mine encompassing the areas containing the blast location, number and nature of all intervening passages including any convergences, presence of seals, stoppings or equipment. This determines the progress and attenuation of the blast energy and pressures as they move towards potential refuge station locations (see Section 5.4).

- The location of the refuge station, including its placement in passageways such as cross cuts; distance and exposure to the incoming potential blasts. This determines how the attenuated blast energy and pressure waves that reach area of the refuge location might actually be applied to the station components or walls.

When examining mine explosion test data, there should be careful distinction between the direct impact pressure ("total", including gage and aerodynamic) and the 50% or more lower gage pressure which acts in all directions. All blast pressures are "dynamic" in the sense they are time-varying, but that is a different usage than its meaning of aerodynamic. There is a clear explanation of this made in [7], their sec.5.

Since the terminology used in different test reports over the past 30-40 years varies, this is the semantic equivalence found for blast-induced transient pressures:

Gage = "static" = "vertical" (LLEM instrumentation on vertical surfaces aimed perpendicular to incoming or passing blast fronts)

Total = "dynamic" (early reports) = "wind" = "horizontal" (LLEM instrumentation on vertical surfaces aimed directly at horizontal incoming or passing blast fronts)

5.3 Explosive mixture variation

<u>Methane percentage</u>

LLEM tests have experimented with the effect of methane percentage in the explosive mixture. It is accepted that the "ideal" gas concentration is 9.5-10% methane, which results in the most efficient blast and highest energy. It was shown [3] that when the methane percentage fell below 8%, or rose above about 11%, measured gage pressures at the outby end of the gas zone fell off about 20% from their maximums for the largest (50 ft) gas volume, and quickly dropped with even lower percentages until no ignition occurred. Above 13.5 to 14%, a rapid burning rather than explosion occurred with much lower pressures but with the potential for a propagating flame front.

Since this percentage in an actual scenario is impossible to predict, we plan to use cases in which the methane percentage is in the maximum pressure range.

<u>Gas Volume</u>

Many different LLEM tests have been reported in which the explosive gas volume was varied. The tests most applicable to our characterizations here used a simulated "working end" of a drift passage (roughly 7 ft h x 20 ft w = 140 sq ft), in which that end of the gas volume was stopped by the end face. The tests most useful for this work had the other end of the explosion directed down an open drift passage or the like (i.e. not completely contained, analogous to the "open end of the gun barrel"). However, the distance of the other end of the gas volume was usually varied from a small number like 10 ft (1400 cu ft) to a relatively large amount such as 50 to 60 ft in a uniform passage (7000-8500 cu ft). These were separated by a membrane before ignition. [3] and [1] (single-tunnel LLEM tests #468, 469 & 470). It was found that the max pressures varied fairly directly with volume, as expected, with the max pressures at the largest volume. Examples of the resulting transient gage pressures for the largest such volume were most often in the 20 psi gage range near the blast (at ideal gas percentage), dropping off with distance and passage of open cross cuts (discussed in a following subsection). In other tests, much larger volumes such as a 71-ft long section, which also added sealed end areas of cross cuts, were ignited (still with an open ended main drift), and pressures at corresponding locations were slightly higher (Ref Doc x4).

Since mine working face gas explosions are worst case scenarios in active sections (not near gob seals), we plan to use these cases in which the methane gas volume is that from a 50-60 ft long filled end section and open drift, representing a fairly large volume in the 8000 cu ft range of ideal mixture.

<u>Ignition Point</u>

The location of the ignition point relative to the closed end face of the gas volume dramatically affects the blast pressure in these open-ended configurations (again, considered the most representative for refuge station design). Max gage pressures were reached only when the ignition source is close: (0 ft was 25 psig; 8 ft was 17.5 psig) to the closed “working” or end face of a 50-ft long test volume using the 9.5% max pressure methane percentage [3].

Since a likely source of ignition is near the face in a working mine, in which new material is being exposed by mining heads, we will assume that ignition is in the inby end causing maximum pressures.

5.4 Mine Configuration

<u>Distance from Ignition</u>

The distance from explosion origin generally attenuates the pressure peaks, but this must be considered in conjunction with the presence and number of intervening crosscut passages. In a typical mine layout, there will be intervening cross cuts, either off one side or off both sides of the drift. However, LLEM test #347 [7] was conducted in their C-drift with with at least the first four crosscuts sealed off out to 350 ft outby the face. Crosscuts were located on one side only (at appx 100 ft intervals on center, starting about 50 ft outby the face, but the seals were set into the crosscuts providing a slight expansion volume at their locations. The gage pressure traces at many distances progressing down from the blast origin are shown below in Figure 1 (again, gage pressures do not include the dynamic component, but are more suitable for the likely shelter or station locations off on drifts in cross cuts).

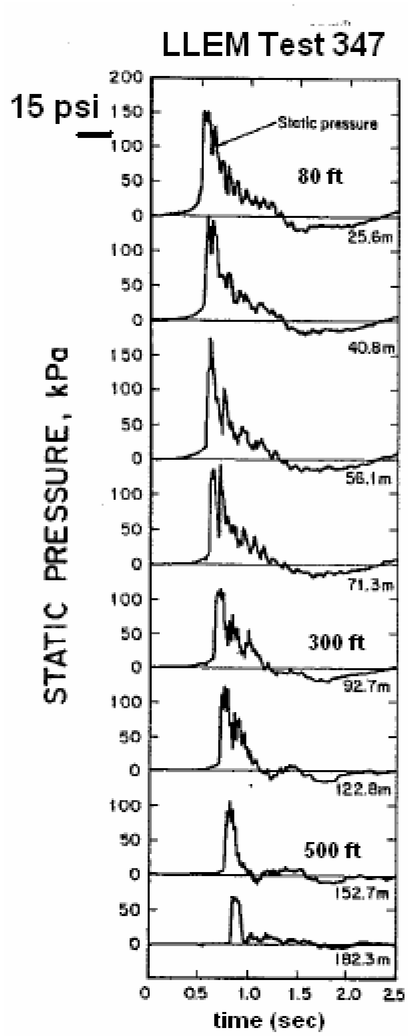

Figure 1. LLEM Test # 347 With Sealed Crosscuts Out Beyond 350 Ft

This shows that the initial pressure peak in the 20+ psi range decreased with distance, and at the 300 ft mark, pressures were about 15 psig. Also the characteristic decaying transient pressure signature is typical, with the peak averaging 0.2-0.25 sec, then decaying towards low values.

Another estimate of the effect of distance only, with a smooth sided passage having no crosscuts at all (not even sealed recesses), we can refer to [1] in which LLEM tests #468, 469 & 470 used the single-tunnel D-drift with gas volumes of 12 ft, 25 ft and 40 ft, resp. This is not a typical or even likely actual mine configuration (smooth "gun barrel"). In #468 and 469, in which explosive gas volumes were lower, there was a 25% reduction at the 500-ft mark, likely due to passage wall/roof/floor friction and heat loss/condensation. For #470, there was little pressure diminution until the 500-ft distance was reached. This implies that there is usually a diminution effect with distance only in smooth tunnels, but for large gas volumes (larger energy), one may not be able to always count on this reduction to be significant, at least outby to 500 ft with large volume explosions.

Effect of Crosscuts

The reductions of blast pressure resulting from passage of open cross cuts or similar crossing passages can be assessed, and are significant. From [1], LLEM tests #484 and 485 used the B-drift which had two-sided intervening cross cuts. We see that peak gage pressures at the 500-ft mark are approximately 1/3 those inby at the face area, with the passage of five crosscuts. Also, in much earlier tests [3], there was a similar factor of 3 reduction at the same distance in a similar configuration of both mine and explosive gas percentage and volume. It seems reasonable to estimate the effect in this form:

$$P_{distance} = P_{origin} \times (\boldsymbol{f}_{cc})^{n} \text{ , where}$$

$P_{distance}$ = Peak pressure at the reference distance
P_{origin} = Peak pressure at the blast origin
$\boldsymbol{f}_{cc}$ = Passage reduction factor for that type of cross cut

The #484 and #485 tests used the end wall (face) vented into the open B-drift with ignited gas volumes of 25 ft and 40 ft passage length resp., filled with ideal 10% methane, and ignited near the face. The [3] tests also included these conditions. This represents as mentioned, a typical situation but with the maximum effects of ideal mixture, reasonably large gas volume, and ignition at or near the working face.

In these cases, passage of five cross cuts and a total reduction in peak pressure to 1/3 of the inby value an average reduction factor per cross cut of about .80 using the above formula. These are subject to variations, but give a good order of magnitude, and clearly show that passage of more than a few open cross cuts of any type leads to significant peak pressure reductions. These tests embodied mostly two-sides cross cuts although in the early tests [3] there may have been some 1 sided cuts if C-drift were used. In other reported data [11], there is reference to other two-sided cross cut passings resulting in a slightly greater reduction per passage (smaller factor than the 0.8 above).

These factors would be a little larger (i.e. cause less reduction) if cross cuts were partially blocked by equipment or partial stoppings. In that case, since a totally sealed passage with the seal very close to the drift (blast route outby the origin) shows small reduction, it would be conservative to estimate raising these factors to approximately 0.9 for major blockage. This is admittedly a great simplification of complex phenomona, but it conveys the general facts. If there is a combination of partially blocked/1-side or 2-sided cuts, these can just be multiplied out in sequence for an estimate.

As an example, if a bulkhead station were located in a cross cut 500 ft outby the explosion (and in sufficiently to avoid direct shock impact), with passage of four mostly blocked cross cuts, using an initial peak gage pressure of 20 psi, that would lead to a bulkhead pressure value of about

$$20 \text{ psig} \times (0.9)^{4} = 13 \text{ psig}$$

This corresponds reasonably well with the results for LLEM 347, in which cross cuts were sealed but with some expansion volume outside the main drift ahead of the seals.

Summary: the likely distance from a blast origin, if at a working face, would be no closer than 500 ft based on mining logistics. Therefore, the principal effect of this distance would be the presence of intervening open or partially open passages (cross cuts or other intersecting drifts). Based on peak gage pressures at a blast originating at a closed face, with the blast vented outby through a single drift with intervening passages, the likely range of origin pressures based on tests would be in the 25-30 psig range or lower. With the presence of at least 3-4 open cross cuts in that 500 ft, gage pressures at the nearest station location would be in the 15 psig peak range (transient peak in the 0.25 sec range) as a working design value. Unusual situations with no open crosscuts or even sealed drifts (only test situations or explosions behind gob seals) could lead to higher pressures, justifying use of a reserve strength capability in bulkhead station design.

5.5 Location And Placement Of Refuge Station

The selection of general location areas for bulkhead-based refuge stations is discussed elsewhere, in which the logistics and mix of fixed and portable stations for rapid personnel access and repositioning with mining progress is addressed. Here, with the distance issue covered previously, the local positioning of the stations based on minimizing blast pressures is discussed. In most mine layouts, the favored position for any station would be in a stub-ended crosscut, possibly one created specifically for such a station.

The primary objective in station location is to minimize blast pressures by preventing the aerodynamic (wind) pressure component from striking the bulkhead wall, thereby avoiding direct shock impact. The relative magnitudes of the direct ("total") pressure vs. the gage (ambient, or "static") pressure value can be seen in LLEM test data and MHSA evaluations such as in test # 506 [12] and 498 [11]. In test # 506 values are high due to the test configuration comprising a totally sealed chamber (crosscuts and main drift sealed by walls). This test setup (annotated) is shown below in Figure 2.

Both tests used very large volumes of explosive gas in the 12,000-14,000 cu ft range[1], also. However, these later tests did use rapid-response pressure instrumentation which could capture total and gage pressure traces vs. time. (Total pressure was measured with gages aimed at the blast direction, called "horizontal", while gage pressures at ribs either in the main drift or in cross cuts at seal walls are aimed away from the blast direction, called "vertical").

[1] 71-ft section outby the face plus portions of crossing passages.

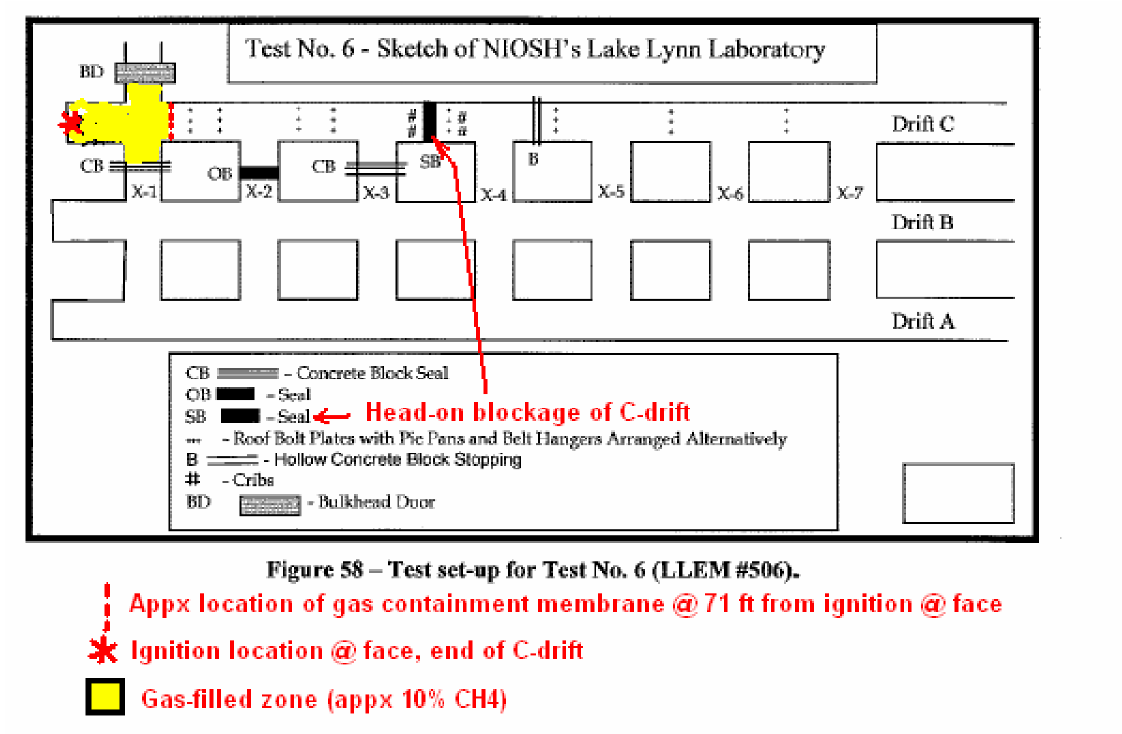

Figure 2. LLEM Test # 506 test setup with Sealed Gas Volume

The test #506 showed a short total pressure peak of 42 psi (gage + aerodynamic) fairly close to the blast at 256 ft outby the blast face (at sealed X-C 3), and a nearby gage pressure sensor at 234 ft read about 30 psig at the same time. The total pressure peak was shorter than 0.1 sec, and the gage pressure peak about 0.12 sec. These test results (annotated) are shown below in Figure 3. This gives the approximate proportion of the total represented by the aero pressure (1/3) in this case. (This test also had a sealed cavity with a walled-off drift, which failed quickly as pressure passed the 5 psi range.) In another well-instrumented test # 498, results were similar and also showed diminution with distance.

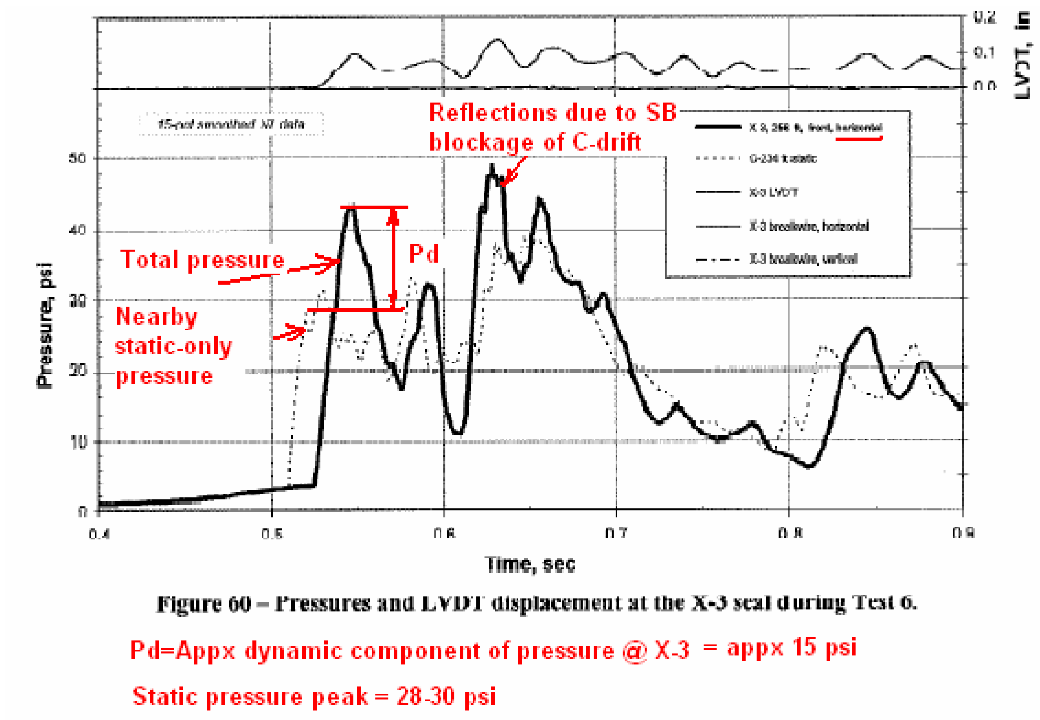

Figure 3. LLEM Test # 506 Showing Relation of Gage and Total Pressure and Reflection Pressure

Therefore, siting the station within a cross cut, which would not likely be in the direct path of the blast wave, is desired. From considerations of shock diffraction and "turning the corner" at the start of such a cross cut or intersecting passage, others [10] have suggested that the sealing wall (in our case, the bulkhead station wall) be away (in from) the main drift rib, to avoid the undesirable effect of a high pressure reflection on the far side of the cut then impacting the wall. Reflected shocks in mines have been observed [12], and these can show total pressure levels much higher than that of the original incoming wave, due to mutual reinforcement of peaks. Thus, a brief study of the shock front behavior at a corner moving in the 1600 ft/sec range (higher speeds for higher pressures), would indicate that the wall should be at least 1.5 and preferably 2 passage widths inset away from the main drift in which an explosion is more possible to occur. A flush location is less desirable since this would expose the wall to potential debris, and also offer no protection for personnel in the main drift for explosions of any level. Further, the junction would have to be truly flush so as not to cause a local shock reflection. There is a good discussion of this plus recommendations in the [10] by MSHA researchers.

The wall should be at least 1.5 and preferably 2 passage widths inset away from a main drift in which an explosion is more possible to occur.

5.6 Effects of Flame Fronts on Refuge Stations

The blast characterization analysis in Sections 5.4 and 5.5 shows that the flame front and resultant pressure wave last for a small fraction of a second. We believe that MSHA's existing flame-resistance requirement [30 CFR 7.24] will govern the design of the exterior components of the refuge station.

5.7 Type of Pressure Appropriate For Bulkhead Refuge Station Wall Design

If the blast wave is incoming down a main or drift, and the refuge is placed in a crosscut 1.5-2 passage widths in, the pressure applied to the wall itself would be much closer to the gage pressure (pressure in all directions at that point, sometimes termed “static”) rather than the “total” pressure which would include the additional aerodynamic loads on objects directly facing the blast wave. Also, if the blast somehow occurred in a drift or other passage not at the mine working end, unless it happened to occur directly in view of the cross cut or passage containing the station, likewise would the aerodynamic component not be a major factor. (In that latter case, there would also be even less “containment” effect from an absent end face, so all pressures would be lower.)

5.8 Potential Blast Loadings to Use for Bulkhead-Type Refuge Station Design

As discussed above, transient blast pressure loadings have been shown to vary widely with the blast parameters. After a thorough review of these and other tests and evaluations of in-mine behavior of methane-only explosions, the transient gage pressure applied to a bulkhead face will be at or below the 15 psig transient trace shown in Fig. DC-1 below, except for very rare cases in which many of the parameters cited all have coincided in their optimum fashion. Thus, this 15 psig/0.3 sec load transient was developed to represent actual “working” load conditions for a bulkhead refuge station considering its placement in the mine. This peak average “top” equals or exceeds the great majority of blast situations, so as to represent a reasonable design basis for the certain survival and functioning of the refuge. This is a common approach in safe design of many structures and vehicles. While magnitudes exceed this in rare circumstances, the many tests at LLEM have shown that the maximum pressure peak time durations from methane explosions are no longer than ¼ or 1/3 second, so that this transient nature of the load for methane-only explosions is well accepted.

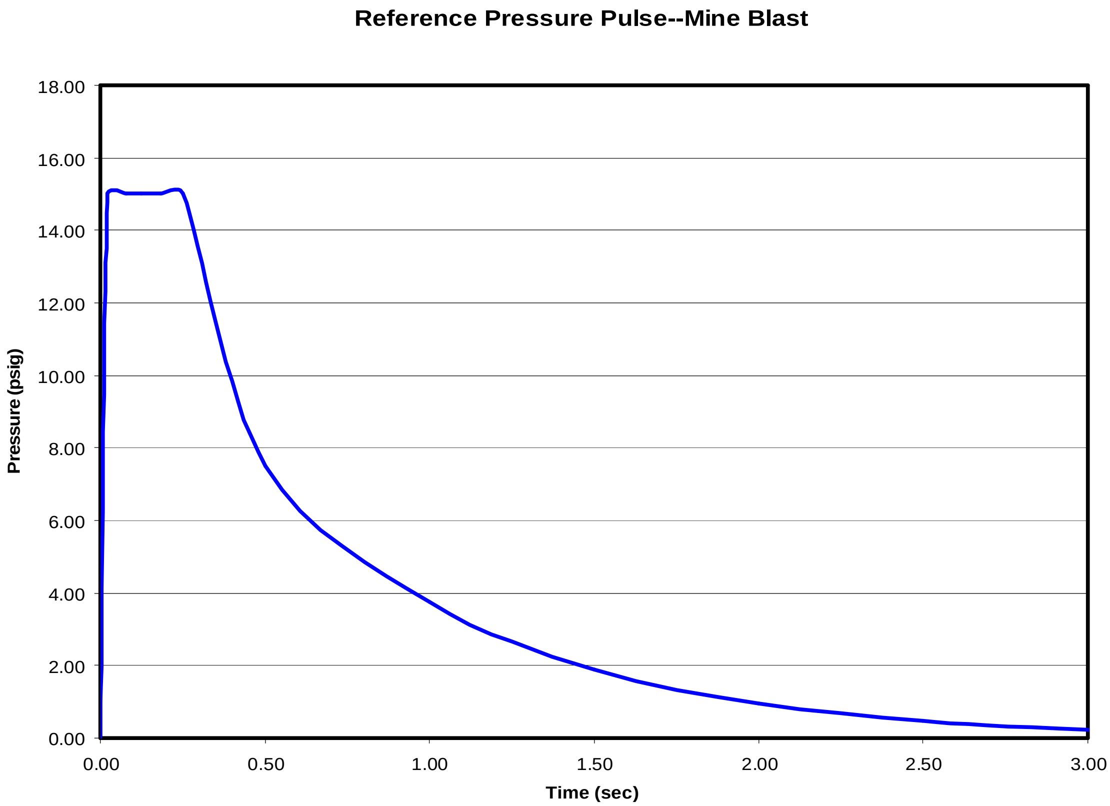

Figure 4. Mine Blast Pressure-Time "Design Pulse" at Potential Refuge Station Bulkhead Locations

5.9 Summary of Blast Characterizations

This section characterizes the major elements affecting transient blast peak pressures. Many of the unpredictable factors such as gas concentration and ignition location relative to the gas were taken conservatively to be their maximum. The others have a rational basis for estimating their contribution, and in the development of the design criteria, these were taken to be consistent with the range of locations, distances, mine configurations, and likelihood of multiple coincidences judged to be representative of the great majority of blast scenarios.