5.4 FLAMES and FORCES

5.4-1 Mapping of Explosion Forces

A discussion on the methods used to map the explosion forces is presented here because this was an important part of the determining of the origin of the explosion, the sequence of blast forces, and the relative magnitudes of these forces. This section describes the effort to map the explosion behind the Omega seals, which began January 27, 2006. By this time vertical boreholes had been drilled near the lowest elevation of the mine at the back of Old 2nd Left in order to re-establish ventilation, and regulators had been installed to control access and airflow.

It took some time to become acclimated to the conditions behind the seals and to become familiar with the patterns of damage produced by the explosion. The area was dark with soot, survey spads[1] were difficult to find (or no longer existed), and a strong creosote smell existed from the effects of coking. Mapping efforts began with an inspection of the top end of Old 2nd Left Section in #2 entry near the edge of the water pool that had been pumped down to keep the newly-drilled ventilation boreholes open. This area of Old 2nd Left is the lowest in elevation. It is also the wettest, due to a sandstone paleochannel[2] that has eroded the immediate shale roof and the now lies unconformably atop the coal seam in this area. Water flows from this sandstone are heavy enough that a deep well turbine pump must be kept running to keep the water level constant. On January 27th the water level was approximately eight (8) feet lower than it was at the time of the explosion. At the new shoreline, methane was bubbling out of the mine floor, registering 0.3% on a ITX gas detector.

A line of stoppings between the #2 and the #3 entries had been used before sealing to provide ventilation to the section. The first three (3) stoppings going up into Old 2nd Left Section had toppled over, but the remnants were in fairly large pieces. The remainder of this line of

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1 Survey stations used underground for determining ones location on a map.
2 A body of sandstone that is an ancient stream channel formed shortly after the immediate shale roof was deposited.

stoppings going from this point up to the waters edge looked as if they had been pulverized – all except for the last two stoppings which we would later learn were partially submerged at the time of the explosion[3]. Later, as water levels dropped further, the stoppings and line curtains which had been totally under water at the time of the explosion were found to be largely intact, although some not completely so.

Photo 1 shows the remains of the second stopping outby from the waters edge knocked down in a southwesterly direction but with the individual 6" hollow-core cinder blocks substantially intact. The wire roof mesh was bent back in the same southwesterly direction and provided corroborating evidence from two or more features to show the dominant direction of the forces of the explosion at this location. Had the stopping not been at least partially submerged, it too would likely have been pulverized.

Photo 1. About 15' outby spad 3716 (STA-2) in #2 entry. Stopping of 6" cinder block, down. Wire roof mesh partially down.

Step by step, cross-cut by cross-cut, entry by entry, clues about the forces of the explosion were observed and recorded. In this manner, the direction of the explosion pressure waves were

[3] Structures submerged in water were afforded protection from the explosion.

mapped. The summary map of this effort by OMHS&T is contained in the *Flames and Forces Map* in **Appendix 5.4-1**, and additional information compiled by the joint mapping teams can be found in **Appendix 5.2.**

5.4-1a Bending of roof pans and plates

Before the end of the first day of mapping a general pattern had begun to emerge about the pattern of preferential bending that had taken place on many of the pans and plates that were bolted to the mine roof. **Square roof pans** (more commonly known as "spider plates") and **round roof pans** (also known as "pizza pans") are supplemental passive support plates that are made from galvanized sheet metal. They were installed on approximately 4-foot centers using roof bolts, and each utilized a roof-bolt plate as the bearing surface for the **roof bolt head.** Additional **wire roof mesh** was frequently installed between the roof pans and the mine roof to supplement the passive roof support. These structures are illustrated in **Photo 2**, below.

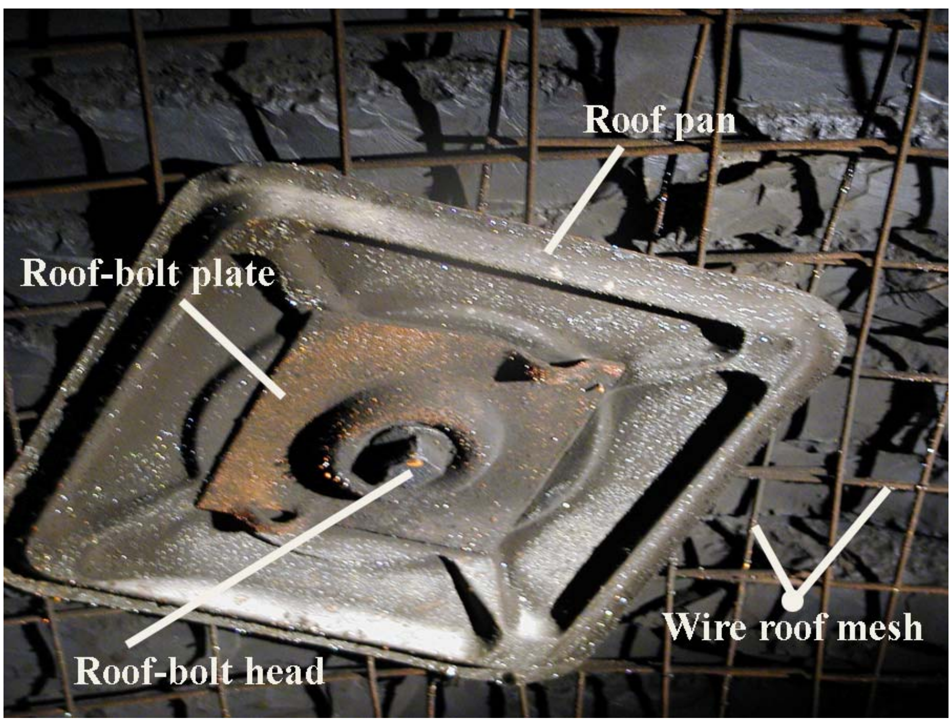


Photo 2. A typical arrangement of roof support, consisting of a roof bolt, roof bolt plate, roof pan, and wire roof mesh—all held against the mine roof by the head of the roof bolt. Square pans (commonly called "spider plates") and round pans (commonly called "pizza pans") are not used everywhere in the sealed area. Nor was the wire roof mesh used everywhere. Where it was used, the blast forces of the explosion altered their configuration in a way that helped us to reconstruct details of the blast.

The morphology of the bending of the roof pans, roof plates, wire roof mesh, and in some cases the roof bolts themselves, as a result of the explosion, provided a wealth of information about the forces that had interacted with them. The direction and the relative magnitude of the forces were determined by the degree of deformation of these materials.

The *Flames and Forces Map* in **Appendix 5.4-1** uses black, red, and blue arrows to indicate the direction of blast forces. Often, the bending was in two or more directions, and in many of those cases the order in which the bending occurred could be determined by the sequence and geometry of bend overlaps.

Flames and Forces Map (see **Appendix 5.4-1**):

1) **Red** arrows: Direction of *initial* forces, when two force directions were indicated and the relative timing could be distinguished from the bending.

2) **Blue** arrows: Direction of *secondary* forces, when two force directions were indicated and the relative timing could be distinguished from the bending..

3) **Black** arrows: One direction of bending. Whether from the initial forces or the secondary forces, could not be proven.

A brief discussion of our interpretation is given below to describe how the origin of the explosion and the relative magnitudes of the forces were inferred. It should be mentioned here that other maps with somewhat different interpretations but equal validity have been produced by other teams; perhaps using slightly different criteria. The absence of an arrow placement on the OMHS&T map does not indicate that the forces were absent; rather just that corroborating evidence to indicate a clear bending direction or sequence of bending was not present at that particular location. When in doubt, the depictions of force directions were omitted. Severe, omni-directional damage to roof pans and plates is indicated by red-shading of those areas on the *Flames and Forces Map* and also in **Map 1.**

Unidirectional bending

The simplest bending morphology of roof pans was one fold in one direction, and this consisted of either corner bending or edge bending, at angles ranging from 45 degrees to 180 degrees from the horizontal[4]. When the majority of bent pans at a particular location were generally in the same direction, this was indicated on the *Flames and Forces Map* by a **black arrow**.

Photo 3. Simple plate bending of a roof pan in one direction. When neighboring pans also showed bending in the same direction this was plotted on the Flames and Forces Map as a single black arrow.

Multiple-direction bending

The roof pans were often bent in multiple directions. Where the pan was bent in two directions the sequence of forces could often be determined by observing the pattern of folds. **Photo 4** shows an example where one end of the square roof pan is folded over the other end. In this case, the first force came from the right and the second forces came from the left. When the preponderance of evidence at a particular location was consistent with this interpretation the sequence of multiple pressure waves could be determined. The *Flames and Forces Map* shows the first-bending with a **red arrow** and the second-bending with a **blue arrow**.

4 Bending at lesser angles was present, but not a good indicator of force direction.

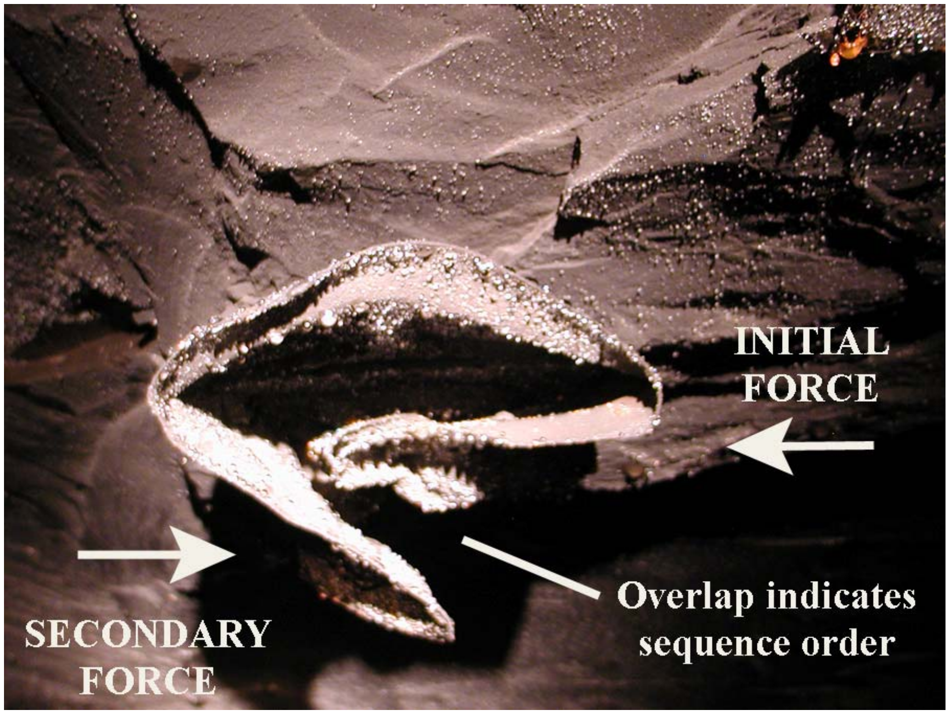


Photo 4. The relative order of initial and secondary pressure waves was interpreted in this example to be from the right, then the left, respectively, based on the overlapping sequence of the pan ends.

A variation of this interpretation of bending morphology is shown in **Photo 5**. Here, there is one direction of bending at first glance but on the side-opposite the bent left edge of the pan the corner of the bolt plate is bent to nearly 90° -- with a hole punched into the roof pan with the same shape and location as the bolt plate—which showed that it had been originally bent together with the bolt plate from the opposite direction (right to left). A secondary wave subsequently straightened the pan back to being flush with the mine roof (forces acting left to right) but left the bent edge of the bolt plate at its original 90° deflection. This type of pan bending morphology was fairly common. Evidently, a primary pressure wave from the right was followed by a secondary pressure wave from the left.

Photo 5 also indicates another complicating factor in that reflections from nearby solid vertical surfaces (such as a solid coal rib or a ledge of uneven roof) can produce localized variations in the bending. In this case the bent edge not identified by an arrow is the edge closest to the coal rib. This bend is likely an effect of local reflections off the coal rib.

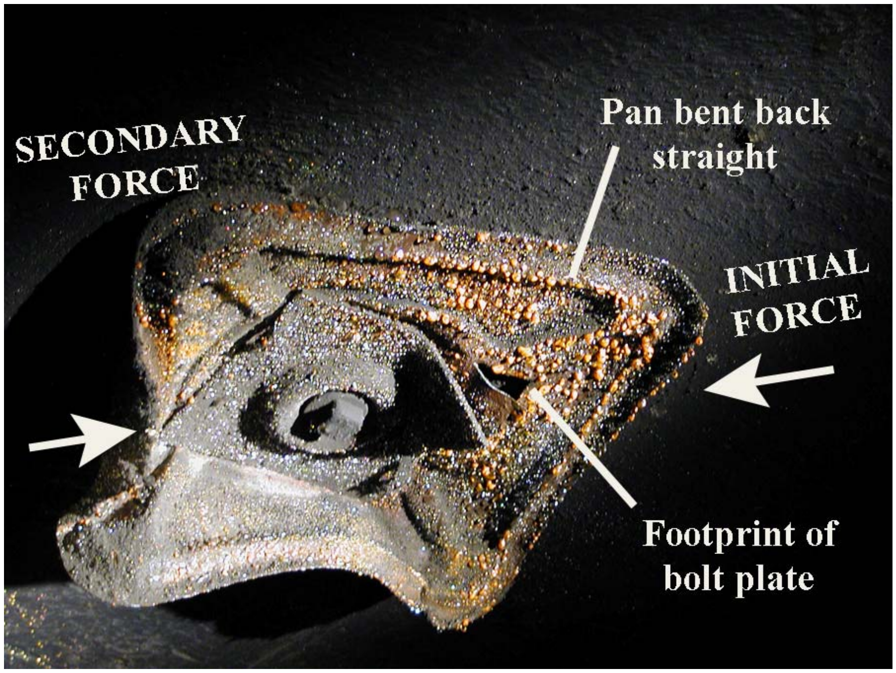


Photo 5. Initial forces bent the right side of this pan and bolt plate, leaving a footprint in the pan where the edge of the bolt plate punched through. This was followed by a secondary set of forces coming from the opposite direction which pushed the bolt plate back flush to the roof but leaving the corner of the bolt plate as originally bent.

Photo 6. An example of a severely deformed roof pan ("spider plate) that was found in the #9 entry just inby Seal #10. This is typical of the degree of bending and damage found between the seals and just after the first line of crosscuts inby the seals. This type of damage was also found in other areas of the mine where there were significant obstructions and where there was first-mining only (no "bottom-mining" done on retreat).

There were many variations in the bent-pan morphology due to local turbulence that complicated the inference on the blast forces. Pans that were located near entry/cross-cut intersections frequently had conflicting indications of the force direction. In order for a particular force direction to be accepted as an indication of a pattern, it was necessary to corroborate the directions of pan bending in a given area and not use just one or two pans. The best data were obtained where the mine roof was fairly even in areas that were mid-way between entry/cross-cut intersections.

Severe, omni-directional deformation of roof pans

A special category of pan deformation included roof pans that were severely deformed in all directions around the bolt-head[5]. This type of plate bending was found in areas where turbulence and physical barriers to the propagation of the blast forces existed, such as gob piles, dead-heads against solid coal ribs, etc. An example of this is shown in **Photo 6**.

Examples of this type of damage generally were found in those areas that were:

1) **not submerged below water** level at the time of the explosion, and

2) were **first-mined, only** (mine roof heights of typically 6-8 ft.).

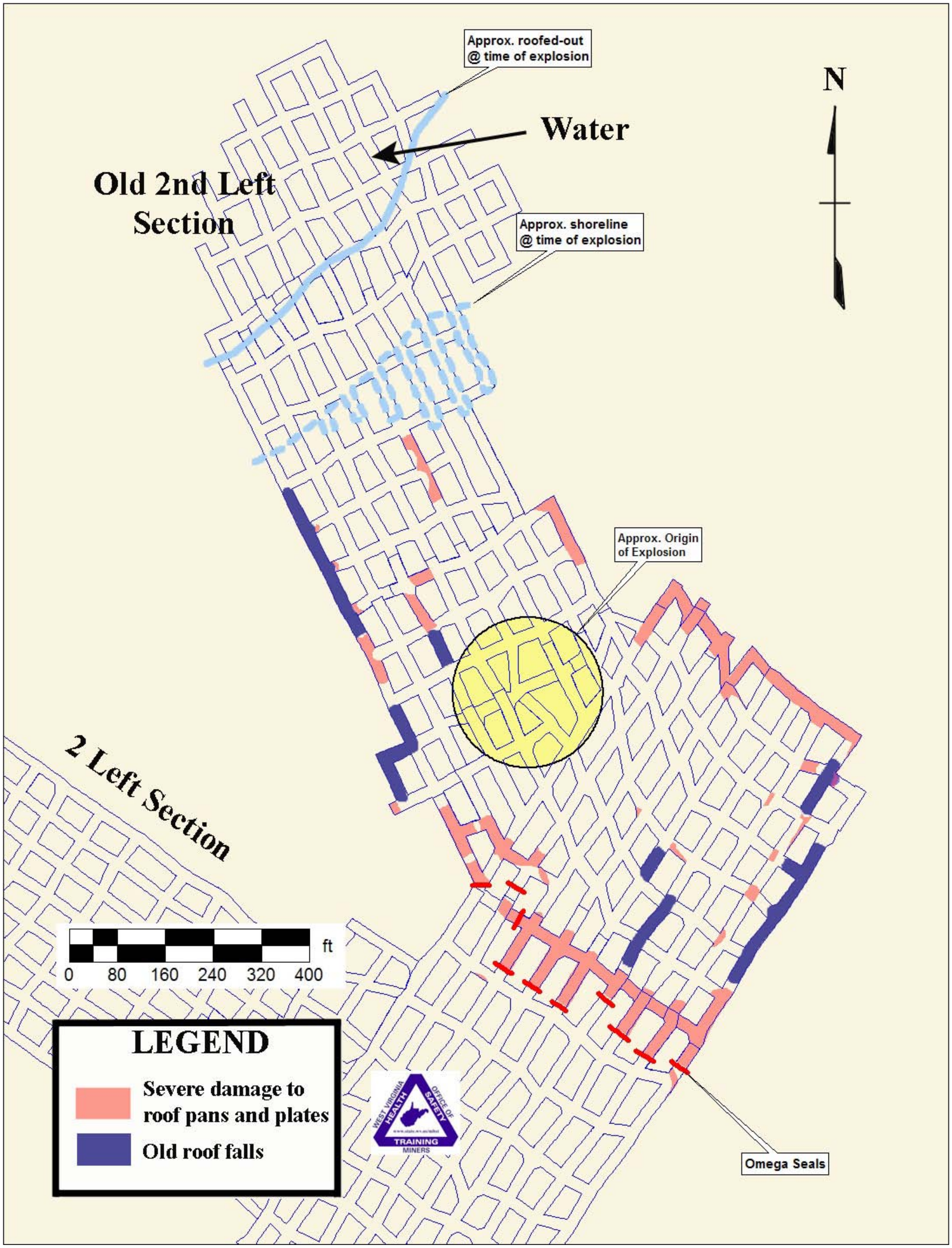
Further, this severe pan/plate bending was prevalent in a given area only if one or more of the following conditions were also present:

1) entry obstructions in the floor such as gob piles which reduced the entry height or opening approximately thirty percent (30%) or more;

2) ragged roof due to bad top; and

3) dead-end headings, reflections around roof falls, 90-degree elbow turns, solid coal face along the outside perimeter of the mine workings, and between the seals to the first line of crosscuts inby the seals.

[5] Bolt plate was often similarly bent



MAP 1. Areas where pan and plate deformation was severe were noted during the course of the mapping effort. These areas were all above the water pool, mostly where bottom-mining had not occurred, and where obstructions impeded blast propagation such as along the solid coal perimeter, next to existing (old) roof falls, and also at the seals themselves.

It should be noted that there were many examples of pans and plates that showed less damage interspersed with these examples of high damage. Clearly, local turbulence played an important role in the type and severity of pan/plate deformation.

5.4-1b Bending belt hangers

Belt hangers were also used as indicators of the direction/magnitude of the blast in several instances. The belt entry was mapped both in front of and behind the Old 2nd Left seal locations for the purpose of documenting the direction and degree of bending of the belt hanger flanges.

Photo 7. An example of a bent belt hanger, which were usually bolted directly to the mine roof with no pan underneath. Their purpose is to provide an anchor point to hook chains to suspend the conveyor belt structure. This is a smaller version of the 4"x 4" belt hanger flanges that were typically used throughout the mine. Originally the angle of the flange was 90° (+ / - 1 degree). This bending was studied as another source of information to interpret blast force direction and magnitude.

Two (2) mapping surveys of these structures were performed. The first survey was performed on February 16, 2006 by two personnel with the OMHS&T and the second was performed over a seven (7) day period from April 5 to April 11, 2006 by a joint team comprised of personnel from Alpha Engineering, ICG, and OMHS&T.

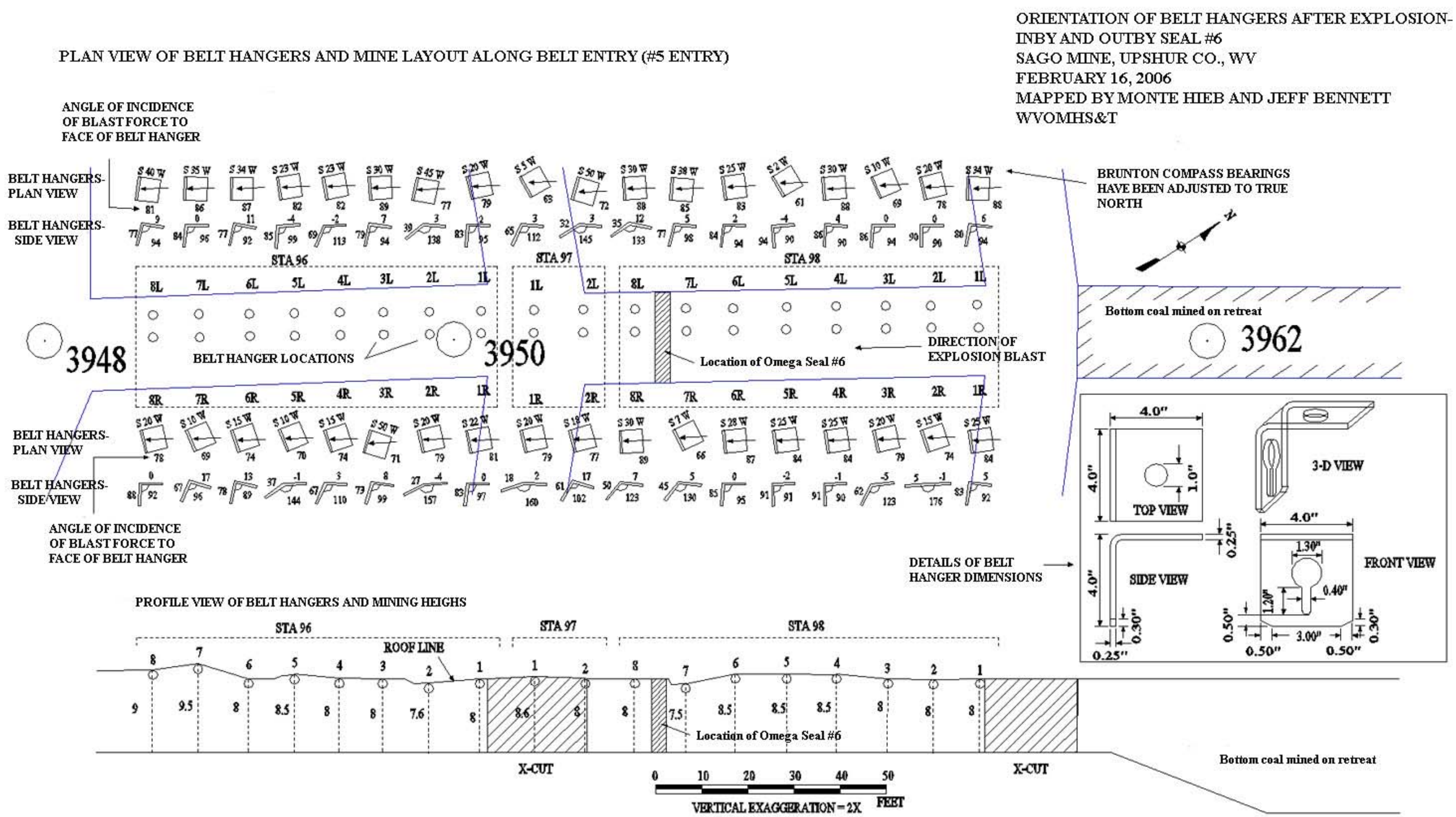


Figure 1. Results of Belt Hanger Survey 1 performed on February 16, 2006. Location is in the #5 entry (former belt entry) in the vicinity of Omega Seal #6. See **Appendix 5.4** for more detail.

Belt Hanger Survey 1

This first effort at mapping the belt hangers started with 36 belt hangers in the #5 belt entry in the vicinity of the Omega seal #6 location—14 of which were located behind Omega Seal #6 and 22 on the front (outby) side (see **Figure 1**).

A larger version of this map is provided in **Appendix 5.4-1**: *Belt Hanger Survey 1*.

Uncertainty exists as to exactly how the hangers came to be bent, although it has been postulated that hangers bent at the "keyhole" such as shown in **Photo 7** were likely impacted by flying debris. Hangers that were uniformly bent (as most were) likely were bent by air blast pressures[6]. Some of the hangers could have been bent in the course of normal mining operations or during the recovery of the belt structure after mining.

The significance of this information is discussed in **Section 5.4-2**.

Belt Hanger Survey 2

The second effort at mapping the effects of the blast on belt hangers was more ambitious and covered the majority of the remaining lengths of belt entry in the area inby the seals. In conjunction with the prior work that examined the bending of roof pans and plates, this information has provided both the sequence and magnitude of the explosion forces. Maps summarizing graphically the results of both Belt Hanger Survey 1 and 2 can be found in **Appendix 5.4-1:** ***(****Belt Hanger- Maps 1-7)* of this report.

[6] Testimony by Dr. Steve Sawyer

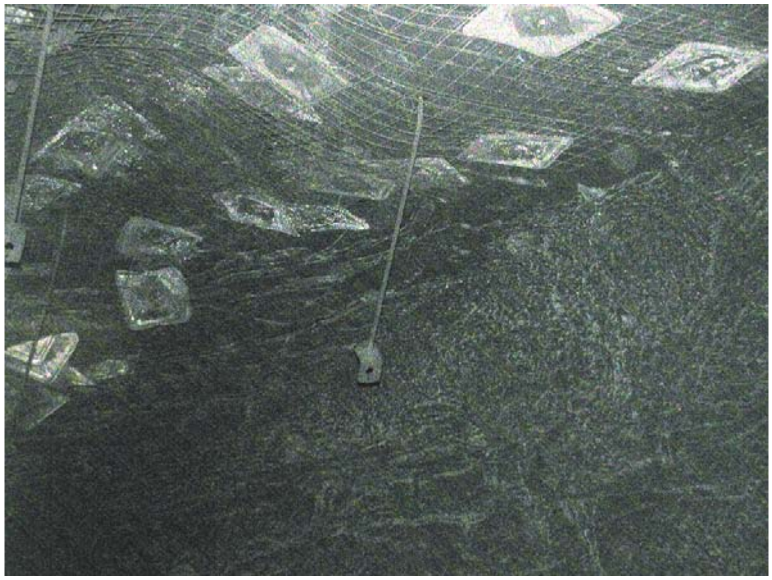


Photo 8. Occasionally, belt hangers were suspended from roof bolts when the height of the mine roof was excessive. In this case, either the last pressure wave or the most forceful pressure wave left these structures bent as shown.

5.4-1c Damage to wire roof mesh

As mentioned previously the wire roof mesh was also used as an indicator of the direction of explosion forces. Often a sense of the primary blast direction could be discerned from the deformation it sustained. An example of this is shown in **Photo 9**.

Photo 9. Wire roof mesh used as an indicator to establish apparent direction of blast forces propagating toward the top end of Old Second Left Section. Photo taken at location STA-3 on *Flames and Forces Map* (Appendix 5.4-1): view facing approximately N 40° E.

5.4-1d Damage to stoppings

As mentioned previously the direction and severity of damage to stoppings can indicate the direction and severity of a pressure wave. Constructed from 6" hollow concrete blocks and also from Omega blocks they are believed to show damage sustained beginning in the 2 – 5 psi range, depending on their construction. Therefore, undamaged or slightly damaged stoppings were used as a guide to areas that experienced low explosion pressures[7]

Photo 10. Remnants of a stopping in an area outby the seals.

5.4-1e Variable damage

Detailed mapping of the Old 2nd Left sealed area showed varying levels of damage, ranging from mild to severe. The damage was found to be less severe in areas that had a high mining height due to bottom-mining[8] where the resultant mining heights averaged approximately 12-15 feet (as compared with normal mining heights of approximately 6-8 feet). **Section 5.4-3** of this report illustrates bottom-mining in greater detail. Outby the Omega seal location plate bending was predominately unidirectional and away from the seals. Pressures dissipated fairly rapidly,

[7] Or, alternately, where explosion pressures developed more of less equally and at the same time on both sides of the stopping.

[8] Mining of a lower coal split by ramping down and recovering it on retreat mining. Doing so approximately doubled the normal mining height in those portions of the sealed area.

but by the time they reached 59 block[9] they still carried enough pressure to pick up and carry a 1500 pound battery charger approximately 120 ft down the track entry.

5.4-1f An area of conspicuously low damage

The bending of roof pans and plates occurred in areas that were first-mined, only, and this appeared to be the rule for most of the sealed area[10]. The area encircled on **Map 1** was the exception. Comprising an area approximately 250-ft in diameter this area is also shown shaded in yellow on the Flames and Forces Map (**Appendix 5.4**). It was conspicuous in the relatively light damage sustained there in the explosion, compared to the adjacent and surrounding first-mined areas. [11]. The first-force bending directions generally radiated outward from this location. This is also the general location where the explosion is believed to have originated. A brief discussion in **Section 5.4-2** contains more details.

[9] Approximately mid way between spads 3901 and 3923
[10] Except for the top end of Old 2nd Left section which was submerged below water at the time of the explosion
[11] Areas that were not second-mined sustained higher velocities, based on a comparison of relative amounts of damage.

5.4-2 Origin of Explosion

Until mine recovery efforts made it possible for investigators to re-enter the mine there was a general feeling that the explosion may likely have originated in the vicinity of the Omega seals. This belief was based on preliminary information picked up through the mine rescue teams. The seals were gone, and the debris field pointed outby. Some degree of gas build-up around the seals was noted in pre-shift reports. The seals were built at the highest elevation of the sealed area so if the mine gases had stratified according to their densities at the time of the explosion the area around the seals logically would have had higher methane concentrations. Suspicions about lightning suggested that an electrical conductor may have been involved. Incomplete removal of the wire mesh over the seals prior to construction could have provided an electrical path past the seals, but further investigation showed that there was no continuous metallic bridge across the seals.

5.4-2a Origin location

What was found during the course of the investigation, however, was that the explosion originated approximately 1/3 of the way into the sealed area at a distance of approximately 350 feet inby from the closest seal (#1 seal) and 700 feet from the farthest seal (#10 seal).

The primary criteria used to arrive at this conclusion were:

1) Conspicuously low damage at this location, despite the fact that there was first mining, only[1]

2) The general direction of the blast forces away from this location, as indicated by the magnitude and direction of bending of metal

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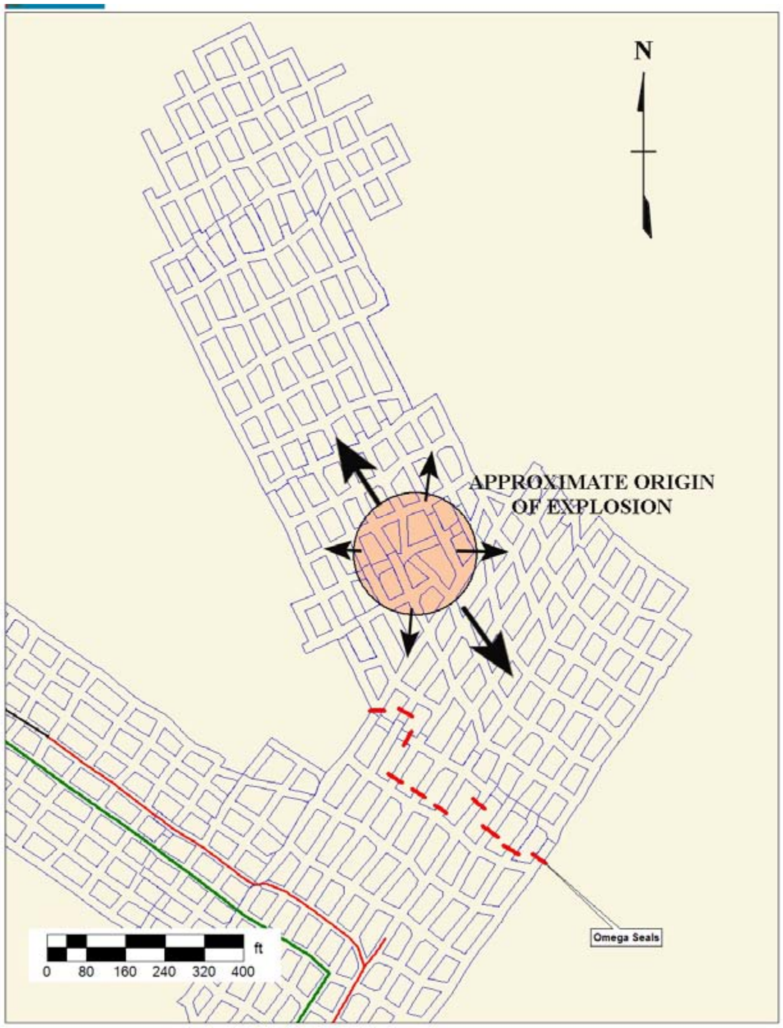
[1] Areas that were bottom-mined on retreat showed approximately double the entry height and generally sustained significantly less damage as a result (see 5.4-3).

roof structures, damage to ventilation stoppings, and standing support structures.



Map 1. The explosion is believed to have originated in the vicinity of the area encircled. The initial blast forces generally radiate outward from this location. It is also an area that has relatively slight damage.

It may seem counter-intuitive that the origin of the explosion should be in a location that suffered only minor damage but this is relatively common in underground methane explosions. One way to explain this is that the explosion from a spark ignition in a volume of gas begins slowly and then grows as a *deflagration.*[2] The flame front accelerates and increases in intensity as it consumes fuel and propagates outward from the origin. This behavior is very different

[2] A combustion wave propagating at **subsonic velocity** relative to the unburned gas immediately ahead of the flame, i.e. the burning velocity is smaller than the speed of sound in the unburned gas; *GexCon- Gas Explosion Handbook.*

from a *detonation*[3] from high explosives like dynamite or TNT which starts out at a high velocity at its origin.

The mapping and analysis of the pattern of damage over the next several weeks and months tended to confirm that the first explosive forces radiated outward from this general location (see, **Appendix 5.4-2:** *Flames and Forces Map*).

Several sets of 5" x 6" x 30" 4-point cribs built at this location remained standing, in whole or in part, after the explosion. The low amount of damage in this area was unique in this respect, except for areas that were underwater at the time of the explosion or had been bottom-mined.

As the investigation continued and the significance of this area became more apparent, investigators began looking in this region for items and features that were unusual or unique in their occurrence and that may have had a connection to the explosion. Two such features were investigated.

5.4-2b The "anomaly"

Near spad 4010 and in the vicinity near where the explosion originated were a series of straight tracks in the roof that could not easily be explained. As such, it was difficult to dismiss their involvement or their significance as they were unique features, at least at that time. Nearby and just north of spad 4028 a second set of similar tracks existed. They are referenced in **Map 1A** as "Anomaly 1" and "Anomaly 2". These tracks were unlikely to be of manmade origin.

Experts were brought in to examine the tracks in-place in the mine roof. Later, samples were cut out of the roof for further analysis and testing. OMHS&T requested a senior geologist with the West Virginia Geological Survey to examine one of these samples. A brief report was written, a copy of which is in **Appendix 5.4-2:** *Evaluation of Roof Anomaly*.

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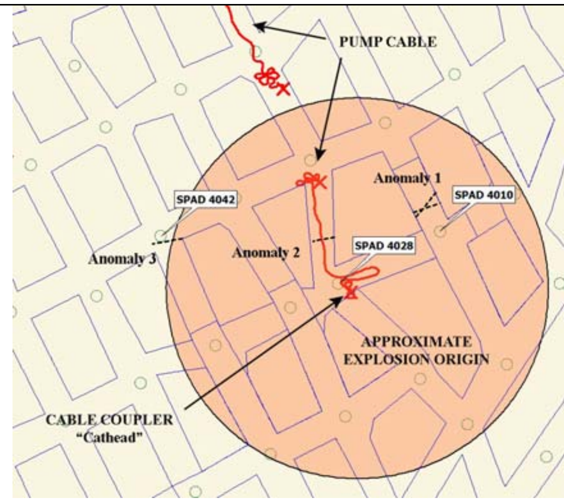
[3] A combustion wave propagating at **supersonic velocity** relative to the unburned gas immediately ahead of the flame, i.e. the detonation velocity is larger than the speed of sound in the unburned gas; *GexCon- Gas Explosion Handbook*.

	
Photo 1. These tracks in the mine roof are near the suspected explosion origin. They were examined in detail for possible evidence of involvement.	**Map 1A**. General location of "anomalies 1, 2, and 3" and part of an abandoned pump cable located within a zone where the explosion is believed to have originated.

Interest waned somewhat when nothing unusual about their composition was discovered. A third "anomaly" was discovered nearby at spad 4042 and at approximately the same stratigraphic level in the roof as the others (diminishing their uniqueness), and geological analysis suggested they were simply an unusually straight cast of a plant fossil. In the end, there was no evidence that these unusual features were anything more than just unusually straight fossils casts.

5.4-2c The pump cable and cable coupler

Another feature that was and continues to be investigated is a pump cable that terminates at a "cathead" (cable coupler) in the general vicinity of where the explosion is believed to have originated under an extensive assortment of roof mesh. This cable was eventually traced back to an abandoned pump that was submerged in water at the top end (back) of the Old 2nd Left section. The cable was broken in three (3) places and was lying with and tangled up among scattered crib blocks and other debris along much of the outby half of its length.

The cable lengths are numbered 1 through 4, with the piece terminating at the cable coupler being length #1. Through the work of John Collins, OMHS&T Inspector, and others, the cable lengths were determined to be approximately as follows:

Lengths of pump cable laying

Cable ID	Length	Comments
#1	199.6’	Outby end terminates with cable coupler near spad 4028
#2	188 ‘	Intimately tangled with crib blocks on floor
#3	~93’	Brattice curtain looped around outby end at spad 4089
#4	~812’	Inby end terminates at pump 3 breaks inby spad 3713
TOTAL	~1293’	

There is reason to believe that the pump cable was intact in one continuous 1300-ft. length (approximately) at the time of the explosion (see **Appendix 5.4-2**: *Description of Pump Cable Lengths and Associations).* If so, it represents a potentially insulated conductor running parallel to a wire mesh that could have developed a different potential in a lightning strike environment. Lightning produces transient voltage surges on metal structures underground (like the wire roof mesh) and if there is a different ground nearby, or if there are discontinuities in the structure, sparking can occur. The pump cable could also have played no role in the explosion at all. In other instances, potential differences could have been produced simply by the conduction of lightning current through rock strata and discontinuities could have caused sufficiently energetic sparks to ignite critical methane gas pockets[4].

Whether the pump cable played a role in the ignition is not yet known but it remains an item of interest simply because it terminates in the general region where the explosion is thought to have originated.

The pump, pump cable, and wire roof mesh are discussed in more detail in **Section 5.5-3i**.

4 H.J. Geldenhuys, & A.J. Eriksson; Research into lightning-related incidents in shallow South African coal mines; Proceeding of the 21st Int’l Conf. of Safety in Mines Reseach Institute, October, 1985, p. 775.

5.4-3 Forces on the Omega seals

Ten (10) seals that were built to isolate the mined-out Old 2nd Left Section from the rest of the Sago mine were destroyed in an explosion on the morning of January 2, 2006 and there was little left after the explosion. Small pieces of Omega blocks and gray dust were found scattered a considerable distance outby from the seals. Very little if any of the debris field was found inby the seals, consistent with other evidence which indicates the origin of the explosion was a considerable distance inby the seals. Exactly where the seals had been installed was difficult to discern on casual inspection because hitching[1] of the seals was not required. But by locating subtle perimeter lines of mortar and other means all the seal locations were found and detailed maps of the foundation and remnants were made during the investigation. These are described in more detail in **Section 5.2**.

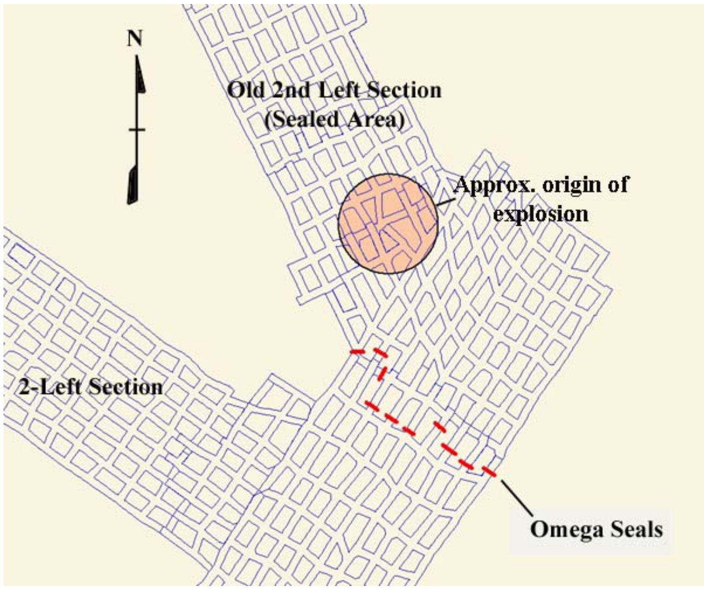


Figure 1. Location of the ten (10) Omega seals that were constructed to seal off the Old 2nd Left Section. Construction was complete on December 11, 2006.

[1] Using mechanical means to create a continuous recessed notch in the mine opening around where the seal is to be installed, being the same width or slightly wider than the seal, and into which the seal is seated.

It is evident that the forces that destroyed the seals far exceeded the ability of the seal to withstand the forces, and the overpressures are believed to have been more than double the 20 psi pressure for which the seals were designed, and possibly much higher. A variety of factors such as the local site conditions and mine geometry can affect the forces that are produced in a mine explosion. These will be considered briefly here, both to serve as a partial explanation as to what may have happened and as information for consideration in future seal constructions.

5.4-3a Applicable regulations on seal construction

In March 11, 1996 a MSHA rule entitled "Safety Standards for Underground Coal Mine Ventilation" defined the standards by which seals were to be built. Among other provisos, 75.335 (a) (2) of that document allows the use of "alternative seals to create a seal if they can withstand a static horizontal pressure of 20 pounds per square inch…" This was the criterion for explosion pressure that was in effect at the time of the previous tests of Omega block seals. This criterion was also in effect when these seals were approved and installed at the Sago mine in December, 2005.

5.4-3b Prior testing of Omega block seals

Seals constructed of Omega blocks are considered "alternative seals." They are made from lightweight fiber-reinforced cementaceous materials, and were originally used for the construction of ventilation stoppings in underground mines. More recently Omega blocks have been approved for use in the construction of mine seals [2].

Results of explosion tests of seals constructed of Omega 384 block are described in publications [3] written between 1990 and 2003 and document the ability of these alternative seals to withstand explosion pressures equal to or exceeding 20 psi static pressure. This standard is the same for coal mines across the country[4].

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[2] WVOMHS&T and MSHA have suspended approval of mine seals constructed from Omega blocks pending further review.

[3] "Omega 384 Block as a Seal Construction Material", C.R. Stephen; 1990, "Designs for Rapid In-situ Sealing," M. Sapko, E. Weiss, J. Trackemas, C. Stephan; 2003.

[4] An exception may be a 1921 law that requires 50 psig for sealing connections between coal mines on federal lands; D.W. Mitchell, Explosion-proof Bulkheads, USBM RI-7581, 1971, p. 2.

Tests of the Omega block seals were performed at the Lake Lynn Experimental Mine (LLEM) which is a retired underground limestone mine that has test entries carved out in room-and-pillar fashion to simulate the layout of a typical coal mine. The test layout is illustrated in a general way in **Figure 2**, consisting of an entry that is a dead-end on one end and open on the other (D) and with cross-cuts A, B, and C at approximately right angles to it.

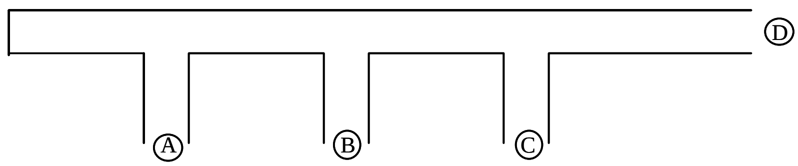

Figure 2. Generalized layout of facility used to test Omega block seals. A, B, and C are cross-cuts. D is an entry.

For the original testing, the Omega block seals[5] were constructed in crosscuts adjacent to an entry where an explosion was created, as shown in **Figure 3**. This was basically an "open chamber" explosion test whereby the blast forces that passed by the crosscuts as they traveled down the entry were allowed to escape from the entry without any confinement. Although this does not simulate the conditions of an explosion in a small sealed area very well, it did satisfy the purpose and conditions of the test at the time-- namely the ability of the Omega block seals to hold forces produced by at least 20 psi static pressure.

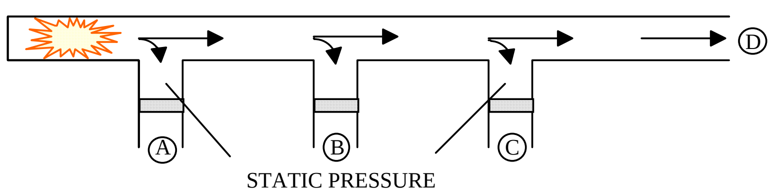

Figure 3. This is a schematic of the "open chamber" test of Omega block seals. Set in the cross-cuts, the seals A,B, and C are subjected to a 20 psi "side-on" pressure from an explosion located at the back of the entry.

The MSHA report documenting these tests stated that "20 psig (was) a suitable performance characteristic for identifying the flexural strength requirements of seals constructed in

[5] First published document for general circulation was entitled: OMEGA 384 Block as a Seal Construction Material, C.R. Stephan, P.E., MSHA, Report No. 10-318-90, November 14, 1990. The actual test at that time involved four (4) seals.

underground coal mines".[6] An explosion test was conducted on Omega block seals on October 10, 1990 utilizing a pressure pulse of approximately 20 psig. Each of the seals survived this test.

On the morning of January 2, 2006, the Omega seals at Sago underwent their own test, and this time all failed catastrophically. Were the original test results wrong? Were the seals constructed improperly? Or was the explosion considerably higher than 20 psi? These are some of the questions investigators set out to answer with the underground mapping effort and with a series of additional explosion tests on Omega block seals that were conducted in the following months at Lake Lynn Experimental Mine.

5.4-3c Additional seal testing at Lake Lynn

In order to re-evaluate the performance of Omega block seals, explosion tests were performed which examined the seal's performance two ways. First, tests were performed on Omega block seals that were constructed using materials and methods in accordance with those recommended by the manufacturer. Second, tests were performed on Omega block seals that were constructed with certain deviations that related to preparation of the seal foundation and application of the mortar in the vertical joints between blocks. This second scenario was intended to address differences with the actual seal construction methods at Sago, whether perceived or proven. A series of six (6) explosion tests were performed between April 15 and October 19, 2006. The results of these tests await final analysis and publication by NIOSH, therefore this report will not attempt to detail these test procedures and outcomes, but some general observations and comments will be offered. Because the test results have not been officially released, the following observations should be considered preliminary.

<u>Summary opinion of OMHS&T with regard to the Preliminary NIOSH (LLEM) Test Results</u>

- The Omega Seals when built as recommended by the manufacturer were capable of withstanding explosion pressures in excess of 20 psi, static.
- The Omega Seals, as they may have been modified in the Sago constructions, were capable of withstanding explosion pressures in excess of 20 psi, static, and

[6] OMEGA 384 Block as a Seal Construction Material, C.R. Stephan, P.E., MSHA, Report No. 10-318-90, November 14, 1990, p. 4.

- In order to replicate the degree of seal damage, roof plate bending, and debris scattering as occurred at Sago, explosion pressures much higher than 20 psi are required.

Among the important things that were demonstrated in the LLEM Tests were the effects of dynamic pressure and pressure-piling on seals that were built across the entry in-line with the explosion[7]. Dynamic pressure is also referred to as velocity pressure or stagnation pressure. Together, static pressure and dynamic pressure comprise the Total Pressure.

Total Pressure = Static pressure + dynamic pressure

In addition to the expansion of gases in a closed chamber which creates an inflation pressure (static pressure) there is a momentum reversal when the gases meet in-line obstructions and are reflected back (**see Figure 4**). The resulting impulse is in addition to and at least as high as the static pressure. This is the dynamic pressure component. In the recent "closed-chamber" tests at LLEM where average static pressures ranging between 24 and 50 psi were felt in the crosscuts (indicated by **A**, **B**, and **C**), the *total pressure* at the seals erected *across the entry* (**D**) saw approximately 51 to 95 psi total pressure (static + dynamic pressure), respectively. Hence, at this particular range of pressures, and as a general approximation, the forces on an *in-line* seal were about 2x the average *side-on* explosion pressures. [8]

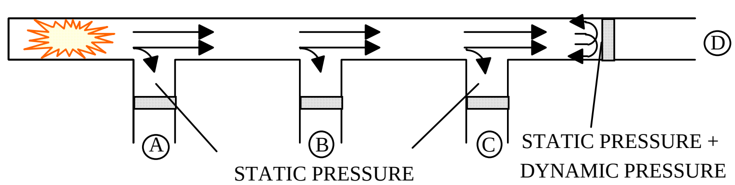

Figure 4. This is an example of the "closed chamber" explosion. A seal placed in-line with the explosion in entry (D) is subjected to static pressure as well as dynamic pressure. In recent explosion tests preliminary results indicate a seal at location D experienced approximately 2x the maximum pressure felt at locations A, B, or C.

When a blast wave impacts a structure at zero angle of incidence, the forward-moving air molecules in the blast wave are brought to rest and are further compressed, inducing a reflected overpressure on the wall which is of higher magnitude than the incident overpressure. When the incident blast wave from an explosion strikes a seal head-on it is reflected. When such reflection occurs, the seal surface will experience a single pressure increase since the reflected

[7] "Pressure-piling" is a local dynamic effect which can cause high local explosion pressures; *GexCon- Gas Explosion Handbook*.

wave is formed instantaneously. The total reflected overpressure at **D** will be more than twice the exact value of the peak overpressure of the incident blast wave as seen in **A, B,** and **C** (see **Figure 4**).

Test six (6) at LLEM produced pressures at the seal at D (**Figure 4**) in the range of 95-100 psi[9]. Only at that level of explosion pressures did the magnitude of damage to roof pans and the amount of damage to seals begin to approach (but not yet equal) that observed at Sago.

5.4-3d The effects of obstructions and bottom-mining

The effects of turbulence and velocity increases at venturi-like[10] constrictions of the mine passages at Sago could also have been a factor contributing to the magnitude of pressures developed by the explosion. As described above, the pressure from a propagating explosion is comprised of two components: static pressure (the inflation pressure of expanding gases equalizing in all directions) and dynamic pressure (the momentum exerted by wind velocities)

A simple expression for dynamic pressure is given by:

$$\text{Dynamic Pressure} = \tfrac{1}{2}\rho V^2$$

where, ρ = density of the air,
V = wind velocity

When the initial pressure wave from a blast propagates down an entry it picks up speed as it consumes fuel. Turbulent mixing of the air and fuel significantly increases the velocity of the flame. Near the location of the origin of the explosion the initial velocity of flame propagation is small, causing relatively little damage from the dynamic pressure. In the case of a methane explosion a flame front moving along a mine entry through areas of bad top, ground support structures, gob piles, constrictions, and other turbulence-enhancers will experience flame acceleration and corresponding local increases in overpressures.

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8 In closed-chamber explosions, some reflection pressures from the in-line seal were felt and these effects must be more closely examined when the official data are available.

9 A preliminary estimate. Also, the seal at location D in Test 6 was an Omega block seal constructed by methods intended to replicate the actual Sago construction.

10 A *venturi* is a tube with a gradually-reduced diameter along its length. In fluid mechanics it is a way to increase pressure without increasing the rate of flow.

Among the factors contributing to the strength of the explosion, and which often are not addressed in seal design, are the effects of hydraulic jumps and turbulence enhanced mixing of air and fuel as the blast wave propagates inside the mine.

A series of ramps and drop-offs in the sealed area of the Sago mine were created during bottom-mining of a lower coal bench on retreat. Although the rock parting separating the two seams was thin enough to allow the top seam to be recovered on advance, it was not feasible to mine the lower seam at the same time because the result is a mining height of approximately 12-15 feet. Mining this entire sequence on advance could possibly have exposed mine personnel to higher risks from falling coal or rock. A plan was devised and followed to recover the bottom coal bench on retreat, where feasible. With the mine roof already bolted the length of exposure to risks associated with working around high coal ribs and high top were thereby minimized.

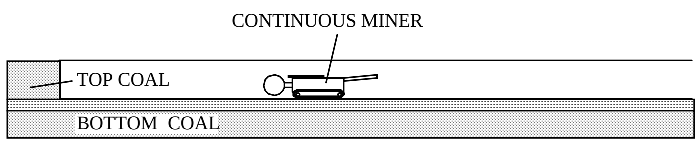

Figure 5. Top coal is mined on advance. Bottom coal is not mined until mining advance in the section is complete and the section retreats. Mining the bottom coal on retreat reduces risks to personnel working under high coal ribs and high top that tends to get weaker with time.

An illustration of this is given in **Figures 5, 6,** and **7**. The top bench was mined first throughout the entire area before bottom-mining commenced (**Figure 5**). Mining of the bottom seam began only as the section was retreating.

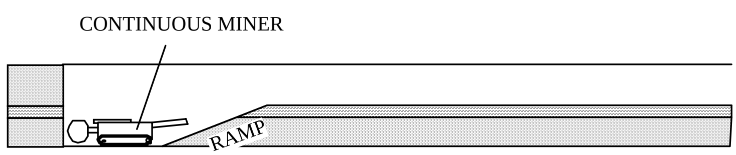

Figure 6. Bottom coal is mined on retreat. The continuous miner ramps down at an angle of approximately 15 degrees and mines through the shale parting to the bottom coal seam in runs of approximately 80 – 300 feet, depending on conditions.

In a simplified way, this is illustrated in **Figure 6** where the continuous miner backs up a prescribed distance and cuts a ramp down off the top coal bench, and mining proceeds until the end is reached. This process repeats and as shown in **Figure 7** occasionally results in small stumps left at the end of a bottom-mining run. Ultimately, all the bottom coal that could be feasibly mined was removed and the ten (10) Omega Seals were constructed outby the last ramp-down in an area that had been first-mined, only.

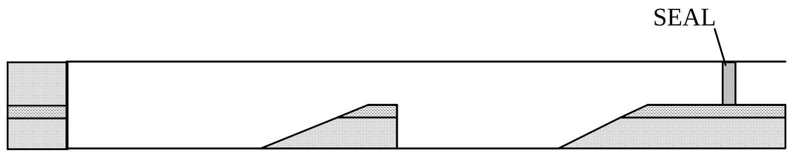

Figure 7. After bottom mining is complete, a series of ramps and drop-offs remain. Ten (10) seals were installed at the top of the last ramp which is the end of where bottom-mining occurred.

Bottom-mining is a fairly common-place procedure when the coal and parting thickness make it feasible and is an accepted practice to facilitate the efficient and safe recovery of all the coal that can be recovered. Bottom-mining is not believed to have played a role in the initiation of the explosion, however the resulting geometry of the mine floor may have facilitated an acceleration of the deflagration as the blast propagated through the region because of the enhanced turbulence produced on the way to the seals. In addition, the last ramp before the seals may have significantly increased the force of the explosion, perhaps by as much as a factor of 4.

Referring to the previous equation that gives a simplified approximation of the dynamic pressures of flow as a function of the air density and velocity,

$$\text{Dynamic Pressure} = \tfrac{1}{2}\,\rho V^2$$

a second equation gives the relationship between cross-sectional area A, velocity of the wind from the blast, V, and the volumetric flow rate Q.:

$$Q = V \times A$$

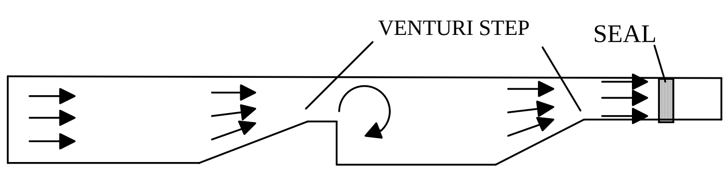

Figure 8. During the explosion blast forces traveling down the entry may have been enhanced by the turbulence and local compression and expansion effects created by the remnant ramps of bottom coal. These forces were obstructed by the seals.

The blast forces were not as great in the bottom-mined areas, as evidenced by the comparatively low damage to roof pans and plates compared to locations that were first-mined only. However, at hydraulic jumps, like at the last venturi step, just inby the seals, (**see Figure 8**) as the cross-sectional area decreases by ½, the flow velocity increases (theoretically) by a factor of 2 in order to keep the same volume of flow (Q) through the constricted region[11].

$$Q = 2V \times ½ A$$

And the dynamic pressure increase by a factor of 4, i.e.

$$\text{Dynamic pressure} = ½ \rho V^2 = ½ \rho (2V)^2 = 4 \times ½ \rho (V)^2$$

Therefore, it is possible that the venturi step just inby the seals could have increased the dynamic pressure by a factor of 4.

It should be pointed out that although this provides a good approximation for the effects of dynamic pressure it is not strictly correct because these are equations for incompressible flow and air is compressible. Because of this the actual velocity increase at the venturi step is probably less than a factor of 4, but compression would result in increased air density which would in turn increase the amount of actual impulse to the seal. Further, what is shown as static + dynamic pressure in **Figure 4** is actually recorded as static pressure at the seal, because wind velocity becomes zero (0) as the blast wave is stopped before reflecting off the seal. The effective total pressures at the seal are therefore reported as *reflected pressure*, which is a value that is somewhat higher than the value for static + dynamic pressures. The net effect of these factors is that, for comparison and illustrative purposes, and at a range of pressures equivalent to as much as a 50 psi static "side-on" pressure wave, a 4-fold increase in additional pressure (we will call it dynamic pressure) is due to the resultant increase in velocity to a blast wave propagating through a ramp that is ½ as high on the top from what it is at the bottom.

Turbulence effects may have also been present where the cross-cuts and bottom-mined entries intersect (**Figure 9**). This is based on the damage that was observed at a number of such intersections where the plate damage was extreme, with little if any damage in the nearby bottom-mined entries between the cross-cuts. Additional turbulence features that could enhance combustion acceleration and the flame speed include things like gob piles that restrict the entry height and areas of bad or uneven roof.

[11] Bottom-mined areas were approximately double the cross-sectional area as normal mining height at the seals.

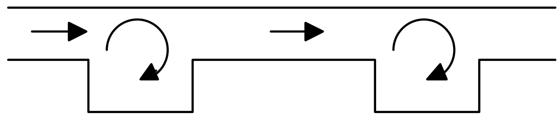

Figure 9. Because little or no bottom-mining was done in crosscuts the propagation of blast forces through crosscuts also encountered turbulence and compression/expansion zones as successive bottom-mined entries were crossed.

5.4-3e Additional evidence of large reflected pressures

As discussed in **Section 5.4-1** there were areas of severe damage to roof pans and plates that looked as if high pressures, temperatures, or both had been at work, generally deforming the pans around the bolt heads in a way that left them looking very much like garden flowers after a frost. In fact, one investigator coined the term “wilted tulip” which is perhaps as good a term as any to describe them.

These areas were noted in red shading on the *Flames and Forces Map* **(Appendix 5.4-1)** and are similarly indicated generally on **Figure 10**. After notes and locations of this style of plate damage were compiled on a map covering the general region of the sealed area it became clear that this type of damage occurred mainly in areas of first-mining, only, and where blast waves impacted at and created pressure reflections at solid boundaries, such as along the outer perimeter of roof falls and areas where entries dead-ended or were butted-off against solid. Also, notably, the area inby each of the ten (10) Omega seals similarly exhibited this degree of pan deformation

Therefore, we can draw two conclusions: first, the explosion forces were of such a magnitude that reflected pressures were very significant (much greater than 20 psi), and second, that the seals did not fail at the instant of pressure arrival, but rather held on momentarily to effectively reflect and amplify the initial incident blast pressure. In the end, the seals did let go catastrophically, but apparently not until presenting resistance.

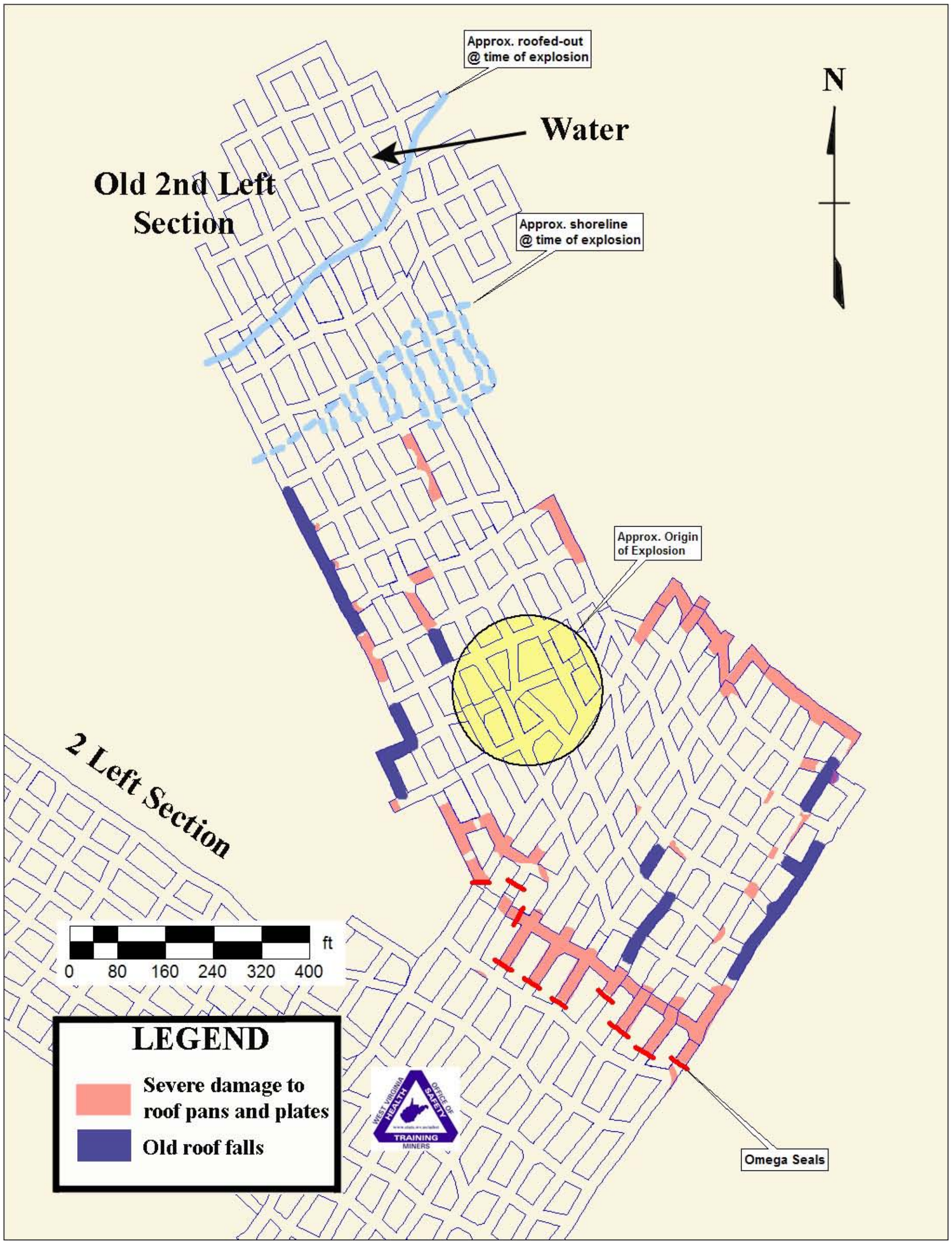

Figure 10. Areas or severe plate damage are viewed as indicators of high dynamic and reflected pressures. Areas shaded in red appear to indicate zones of encountered turbulence and/or obstruction in the path of the blast wave propagation.

5.4-3f Magnitude of explosion pressures

The balance of evidence, both experimental and observational supports the conclusion that the explosion at the Sago mine exceeded 20 psi. There was in fact more damage than can be adequately explained with even a 50 psi explosion. At this writing there is reason to suspect that explosion pressures in excess of 100 psi may have been developed.

A preliminary report by Dr. Steve Sawyer describes the results of bending tests performed on belt hangers and compares them against the measured bending on the same type of structures as observed in the roof both inby and outby seal #6. This preliminary report suggests pressures of at least 60 psi and possibly exceeding 92 psi.[12]

Summary

Mine opening geometry may play a more significant role in the development of explosion pressures in small-volume sealed areas than previously thought. The effects of bottom-mining in Old 2nd Left Section, and the resulting ramps that were created just inby each of the ten (10) Omega seals, may have enhanced the explosion pressures on those seals by at least a factor of 4—perhaps more. In addition, floor obstructions like gob piles, abrupt ledges, and areas of bad top may increase turbulence in an explosion, thereby increasing the combustion rate of a methane explosion and accelerating a deflagration toward a more destructive mode such as a transition to detonation.

Preliminary empirical evidence developed in explosion tests on seals this year at LLEM seems to indicate that even in the absence of the effects of bottom-mining, explosion forces from a blast that exerts 20 to 50 psi static pressure in a "side-on" impact from the passing pressure wave will exert total pressures of at least twice that much in "head-on" impact with a seal or other significant obstruction that is in its direct path. Added together, these factors may suggest our understanding of blast forces as they are applied to seal design and construction may need to be re-evaluated. Further study by way of seal explosion testing and computer simulations utilizing properly validated modeling methods would help increase our understanding of these geometry effects in order to develop more appropriate seal designs.

[12] Preliminary Forensic Analysis of the Peak Pressures on the Seals During the Sago Mine Explosion; Dr. S.G. Sawyer, April 28, 2006—revised May 1, 2006.

5.4-4 Methane Concentrations

From the time the last Omega block seal was completed on December 11, 2005 until the time of the explosion on January 2, 2006 approximately 22 days had elapsed. Concentrations of methane gas (CH_4) emanating from fractures and pore spaces in the coal and surrounding rock strata are believed to have been emitted at an average rate of approximately 18,124 ft^3/day, therefore an estimated 398,740 ft^3 of methane had accumulated by January 2. If this amount was evenly distributed within the sealed area of Old 2nd Left Section at the time of the explosion the average concentration would have been about 13.1 % .

A mine atmosphere is considered to be "outside the explosive range" for methane once the concentrations exceed 15% and/or the oxygen is below 12% [1]. Because the explosion occurred we know for certain that the atmosphere behind the Omega seals had not yet reached these limits on January 2, 2006. To determine the amount of methane involved a series of studies and calculations based on rates of methane liberation and the mass balance calculation of the combustion products were performed.

Two (2) studies were performed by MSHA to estimate the quantity of methane gas behind the Omega seals at that time of the explosion. The raw data from these studies have been used in this report to estimate volumes and concentrations of methane gas at two points after the explosion.

An additional analysis was done by OMHS&T to determine the combustion products that were emitted by the mine after the explosion to estimate the volume and concentrations of methane at the time of the explosion.

5.4-4a Gas liberation tests

Two (2) series of airflow and gas concentration studies were conducted by MSHA and Alpha Engineering to determine the **current** rates of methane liberation in the area of the mine behind the seals. These tests included:

1) A 49-hr. study from February 7 to February 9, 2006

2) A 21-hr study from March 2 to March 3, 2006.

These data were made available to this agency and have been used to help construct a methane liberation rate chart (**Figure 3**).

<u>Method</u>

The quantities and concentrations of methane were measured continuously over a 49 hour period starting at 8:00 AM February 7, 2006 and ending at approximately 8:00 AM February 9, 2006. Two exhaust boreholes that had been drilled earlier to ventilate the sealed area after the explosion were each measured hourly to determine the quantity of airflow and the methane concentrations. The air inlets to the Old 2nd Left (a.k.a the "sealed area") were measured at the same time, and the methane concentrations were determined by subtracting the concentrations at the inlet from the concentrations at the outlet, multiplied by the rate of flow through the area.

The total quantity of methane liberated during the 49-hr. was estimated to be 31,876 ft^3 which is equivalent to a methane liberation rate of 15,613 ft^3/day.

Data from the second study conducted by MSHA was for a period of 21 hours starting at 8:00 AM on March 2, 2006 and ending on March 3, 2006 at around 5:00 PM[2]. Methane concentrations were computed in a similar fashion.

The total quantity of methane that was liberated during the second study was estimated to be 11,430 ft^3 which is equivalent to a methane liberation rate of 13,063 ft^3/day.

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[1] If the oxygen content of the air is reduced down to 12% it cannot form an explosive mixture with methane; *Fire Gases and their Interpretation; P. Mckenzie-Wood, J. Strang; The Mining Engineer, June 1990.*

[2] Approximately 13 hours of no data collection occurred during the sample period.

Accuracy Limitations

The accuracy of these calculations is limited to the accuracy of the measurements and is subject to uncorrected errors in the data, discrepancies, or revisions, and/or OMHS&T interpretation of those data. Some corrections to the data were made, for instance, by replacing values of zero with values of "nearest neighbors" during the periods in which there were no sample data.

These data are given in **Appendix 5.4-4:** *MSHA Methane liberation studies #1 and #2).*

5.4-4b Methane concentrations calculated from the estimated quantity of explosion combustion products

Because the liberation tests do not actually show specifically what the liberation rates were in the 22 days between the date of seal completion of the seal and the date of the explosion, a mass balance calculation was performed for the combustion gases that were ventilated from the mine following the explosion. These results were then compared to the MSHA estimates to see if they fit into a statistical trend in the coal degassing rate over time.

The results of the mass-balance analysis suggests a methane volume of approximately 398,740 ft^3, before the explosion, which implies an average liberation rate over the period of 18,124 ft^3/day or an average methane concentration at the time of the explosion of approximately 13.1%[3].

For purposes of this calculation the fuel for the explosion is considered to have been entirely methane gas, although some minor amounts of other fuels could also have been consumed. The predominance of methane is indicated by very minor C_2H_4 and a Trickett's Ratio of .4 - .5 [4]. Estimates of the total volume of carbon dioxide (CO_2) and carbon monoxide (CO) that were ventilated out of the mine portals were used to infer the original volume of methane that was consumed [5]. The gas concentrations of CO and CO_2 are based on the best data available at the time the readings were taken. Hand-held gas detectors provided CO data values from approximately 8:00 AM January 2, 2006 until 2:45 PM that afternoon. Data for CO_2 were

[3] Assumes uniform gas distribution. OMHS&T estimates the volume of the sealed area is 3,033,818 ft^3.
[4] *Methods to Determine the Status of Mine Atmospheres- an Overview*; R.J. Timco, NIOSH; R.L. Derick, Twentymile Coal Company; Proceedings from the Annual Meeting of SME, 2006. *Mine Fires*; D.W. Mitchell, 1996.
[5] CO_2 concentrations were reduced by 375 ppm to adjust for ambient concentrations.

unavailable so values were estimated from rate of change of CO concentrations over this time period.

Method

The molecular weights of CO and CO_2 were calculated and converted to kg/mole at 1.03 bar and 59-degrees F. The volumes of CO and CO_2 gases coming out the #1 Main Return for a 60-hour period following the explosion (in 2-hour increments) were totaled using an average of seven (7) flow readings[6] out this entry and converted to total weight using densities at 1.013 bar and 59-degrees F.

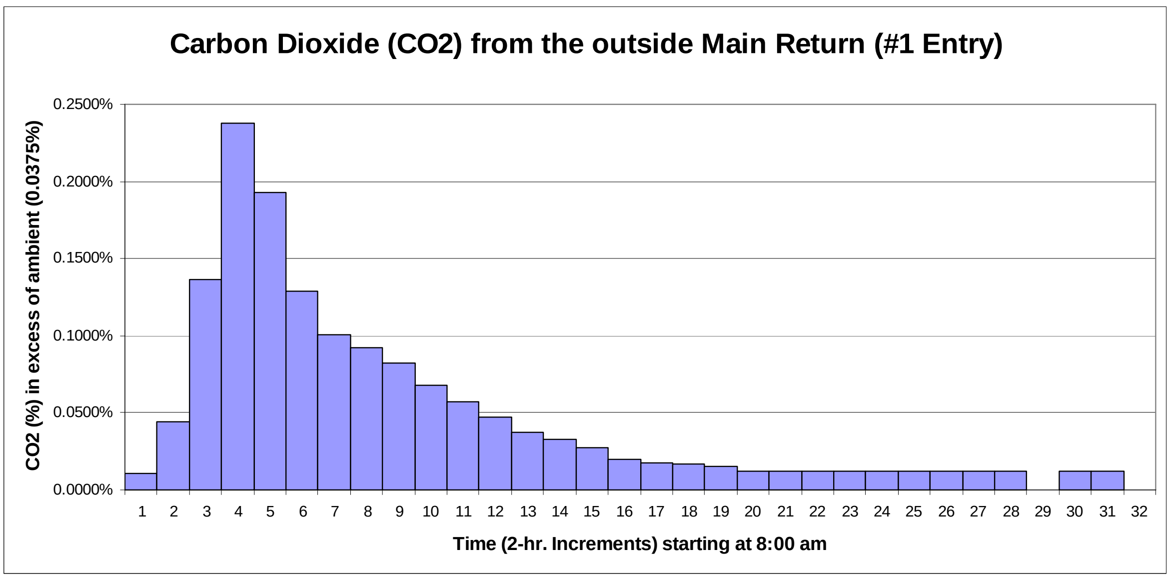

Figure 1. Carbon dioxide (CO2) % concentration as measured at the Main Return (#1 entry). Time units are shown in 2-hr. increments over a 60-hr period starting at 8:00 am on 1-2-06. Volumes have been adjusted for the 375 ppm ambient air concentration.

Next the sum of the CO and CO_2 masses were converted to moles to provide a basis for the moles of CH_4. Volume of the parent methane was then determined by converting back to weight and then finally to gas volume at 1.03 bar and 59-degrees F. A summary of these calculations is included in **Appendix 5.4-4:** *Mass Balance Calculations.*

Accuracy Limitations

[6] Taken between 1-2-06 8:40 AM EST and 1-2-06 9:37 PM EST.

Reliability of these data are limited by the accuracy of the readings of gas concentration, flow volumes coming out the exhausting return and neutrals, and the estimated volume of the sealed area, and the assumptions used in the conversion.

A computer simulation of the pre-explosion ventilation parameters was performed by MSHA (see **Appendix 5.4-4:** *Pre-explosion airflow)* and suggests the blowing velocity of the intake fan in the #5 entry was approximately 172,300 CFM just prior to the explosion. This was used as a starting point, but because of the damage to stoppings and other ventilation controls from the explosion the short-circuits in air which existed at the time of the explosion would decrease the resistance by some factor. For purposes of these calculations the flow rate was assumed to be 185,000 CFM.

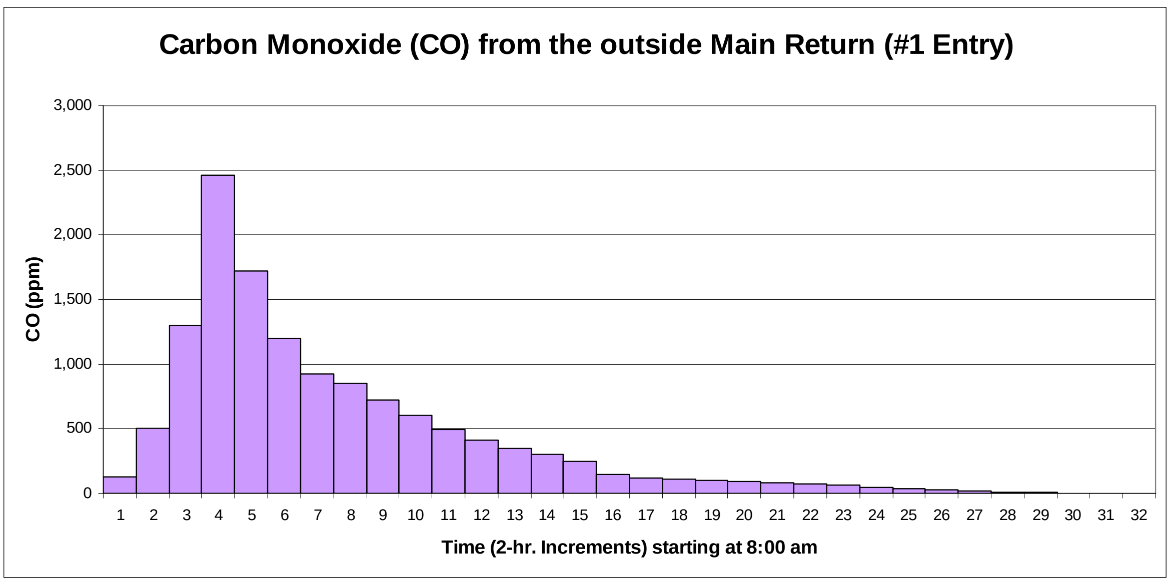

Figure 2. Carbon monoxide (CO) concentrations expressed in "part per million" as measured at the Main Return (#1 entry). Time units are shown in 2-hr. increments over a 60-hr period starting at 8:00 am on 1-2-06.

The sensitive variable in the mass balance calculation is the #1 Main Return flow volume (for which we have only a few actual readings). The #1 Main Return is estimated to have discharged on average approximately 40% of the total exhaust volumes and 85% of the exhaust concentrations during the 60-hr. period. The remaining volumes and concentrations were assigned to the #2, #3, and #4 entries.

Concentration allocations are based on approximately nine (9) sets of hand-held gas detector readings taken at approximately the same time from each of the #1, #2, #3, and #4 entries.

5.4-4c Putting it all together

As a final step the two (2) MSHA and one (1) OMHS&T values for average daily methane liberation volumes were plotted on a chart for comparison. This chart (**Figure 3**) shows a linear rate of decline for methane liberation over the three (3)-month time period.

To check the statistical correlation of the data a linear regression function in Excel was used to generate a best-fit curve and report the equation that describes the gas liberation rate as well as an R-square value (see **Appendix 5.4-4:** *Mass Balance Calculations* for more details**).**

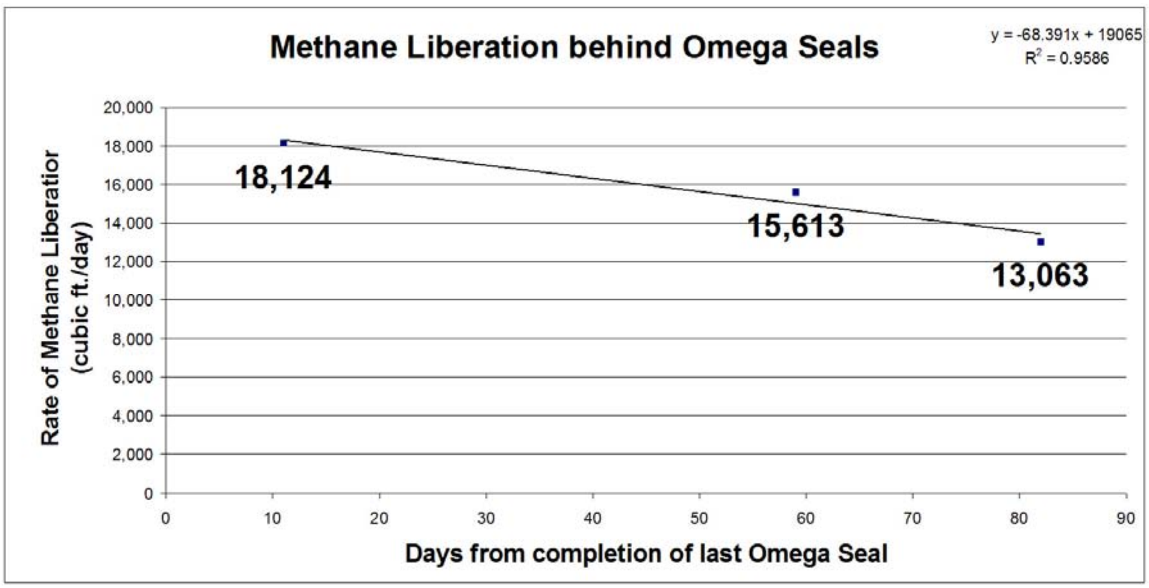

Figure 3. This graph shows the history of average daily methane emissions over time within the sealed area of Old 2nd Left, as determined by an analysis of gas data recorded at Sago Mine.

<u>Findings and Conclusions</u>

An analysis of the total quantities of CO and CO_2 combustion products measured and inferred from the Sago explosion gives the following statistics:

1) The average daily methane liberation rate behind the seals during the 22 days[7] that they were up was approximately 18,124 ft^3 per day.

2) Assuming the methane was distributed uniformly in the atmosphere behind the seals the average concentration was approximately **13.1%**. It has not yet been determined to what extent the gases were stratified so in some regions the concentrations may have been higher than in others.

3) Incorporating the gas liberation data from MSHA suggests that the rate of methane liberation in the sealed area was highest at the time it was sealed and since that time the rate has gradually decreased in volume.

4) Although only three (3) data points are available, these points closely fit a trend given by the linear regression equation:

Rate of Methane liberation[8] = **-68.391x +19,065**

Where "**x** " is the number of days since completion of the Omega seals.

[7] Construction of the seals had been completed 22 days prior to the explosion.
[8] In cubic feet per day

5.4-5 Coking Tests

The extent of the flame can be inferred from the evidence of coke. Coke is the product of the partial combustion of coal in an oxygen deficient atmosphere. In the process, volatile constituents of the coal (including water, carbon monoxide and coal-tar) are driven off and fixed carbon and residual ashes are fused together.

The temperature required for coking to commence varies with the coal but is on the order of 700º F. The flame temperatures during an explosion are approximately 1800º F. Coal exposed to explosion flame does not always coke. Research has shown that coking does not occur when high flame speeds are achieved because the coal is only exposed to these elevated temperatures for several milliseconds. Coking also does not occur beyond the extent of flame.

Coke can only be formed in mine dust that has an incombustible content less than 50 percent prior to the explosion. Explosive forces do however, cause dust dispersion and transport during an explosion with oscillating pressure waves reflected from the surfaces of the mine allowing for dusts and other debris to be moved in all directions.[1]

The Alcohol Coke Test used by MSHA provides one of five results concerning the amount of coke present; x-large, large, small, trace and no coke. The amount of coke is related to the duration that flame was above 700º F and the availability of combustible coal dust. The MSHA analysis on dust samples from approximately 400 locations indicated that the presence of coke inby and outby the old-second-left seals. The highest amount of coke occurred inby the seals within the old-second-left section. Within the old-second-left section the greatest coke was found immediately outby the approximate origin of the explosion in the direction of the seals.

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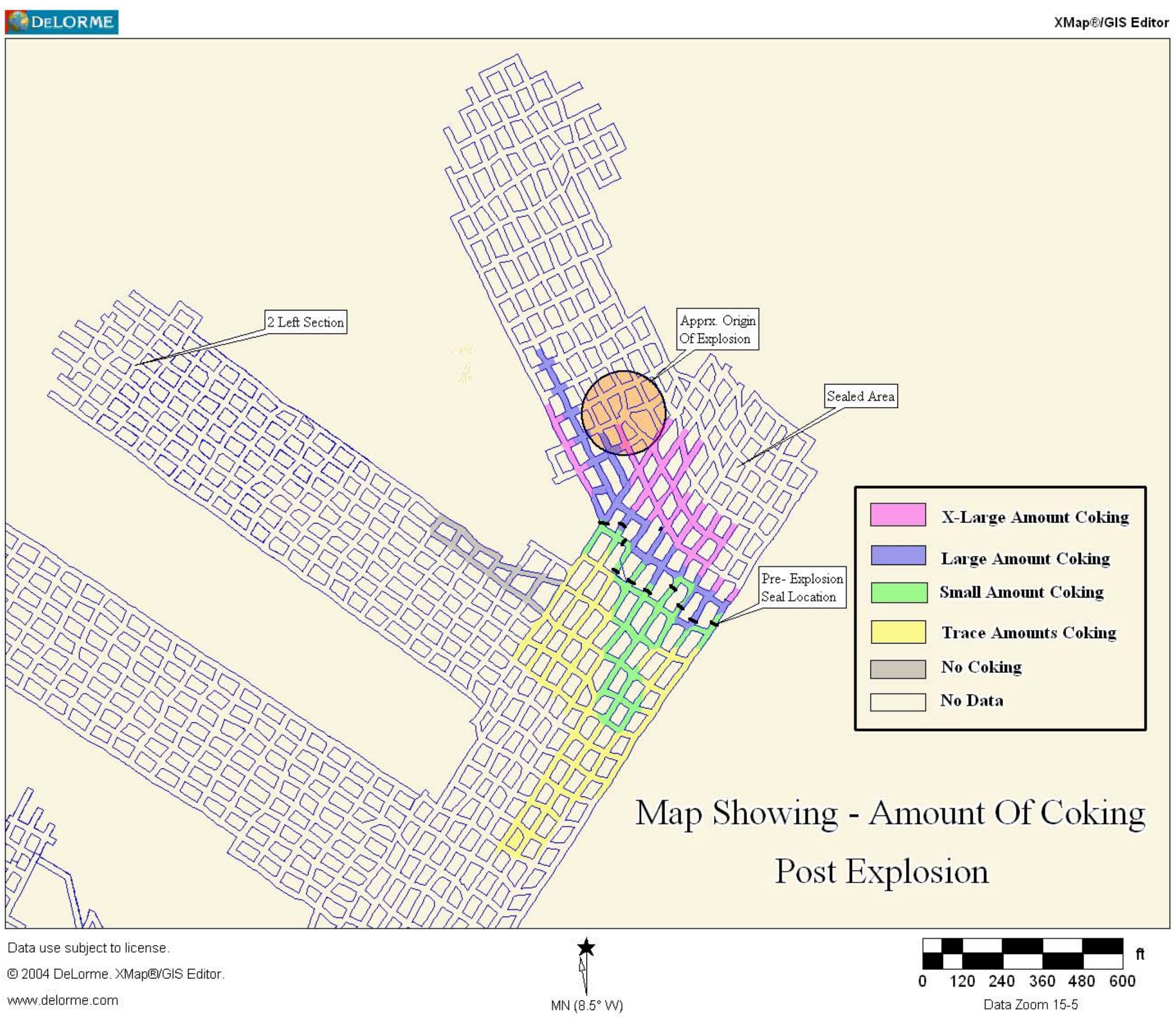
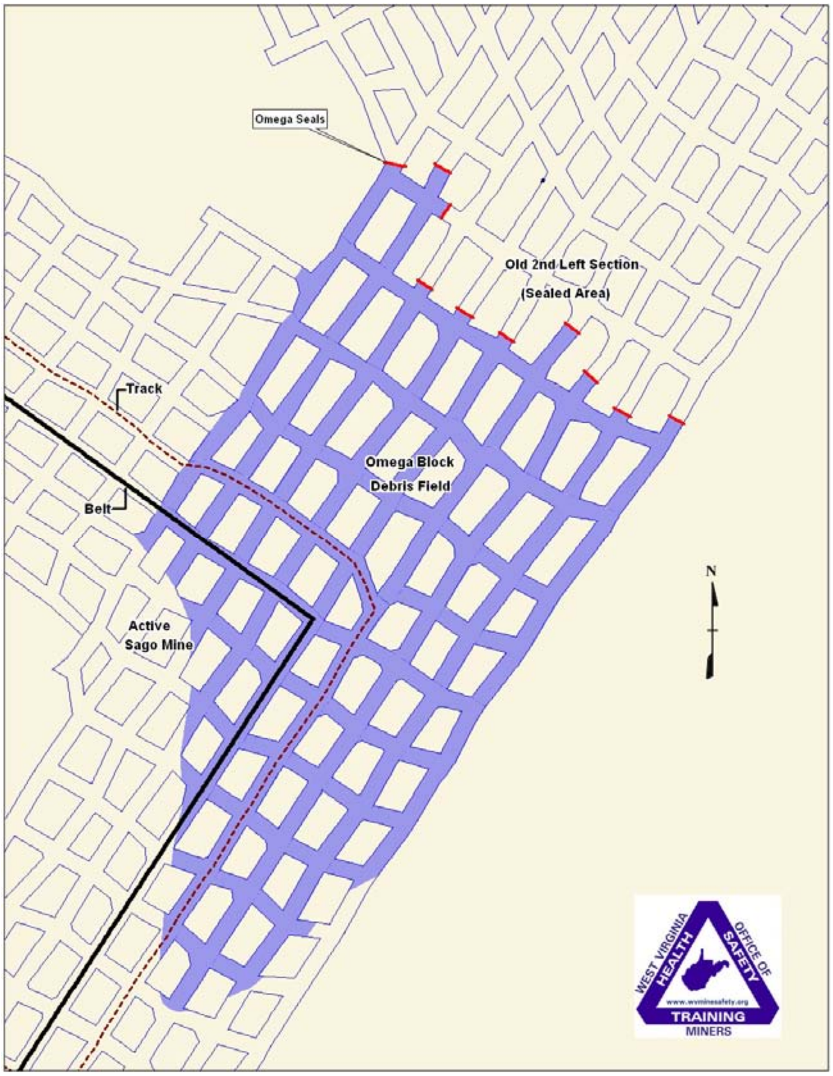
[1] From MSHA document CAI-2001-20-32, Fatal Underground Coal Mine Explosion at No. 5 Jim Walter Resources September 23, 2001

In analyzing the coking map (**Map 1**) the area of x-large coke amount extends from the approximate origin of the explosion outby towards the seals. The distribution of debris (**Map 2**) shows that the bulk of the debris was scattered in a pattern that closely mirrors the coke patterns.

This information supplements and does not contradict the information from the flames and forces.



MAP 1: The amount of coal coking is an indicator of the amount of heat and duration of that heat. The symmetry of the coking trends is similar to the symmetry of the Omega block debris field (see MAP 2).



MAP 2: This illustration shows the approximate distance and symmetry of the debris field created by the ten (10) destroyed Omega seals.