# REPORT
# OF
# GROUND VIBRATION AND AIRBLAST COMPLIANCE METHODS RESEARCH

**By:**

**WEST VIRGINIA**
**DEPARTMENT OF ENVIRONMENTAL PROTECTION**
**OFFICE OF EXPLOSIVES AND BLASTING**

**DECEMBER 31, 2005**

# TABLE OF CONTENTS

## ABSTRACT

The Office of Surface Mines (OSM) has established four monitoring methods for regulatory compliance. Field data collected from large and small coalfield production blasts, blast log data from West Virginia Department of Environmental Protection (WVDEP) Notice of Violations, and damage claim adjustor reports are used to make comparisons between these compliance methods and their differences in measuring the adverse effects of blasting operations.

## INTRODUCTION

Various United States Bureau of Mines (USBM) Report of Investigations (RI), OSM Blasting Guidance Manual, and other technical books and articles identify the blasting impulses required to damage structures. It is very important to define the term "damage" since there are several references to this term in West Virginia Code and the Surface Mine Coal Reclamation Act (SMCRA).

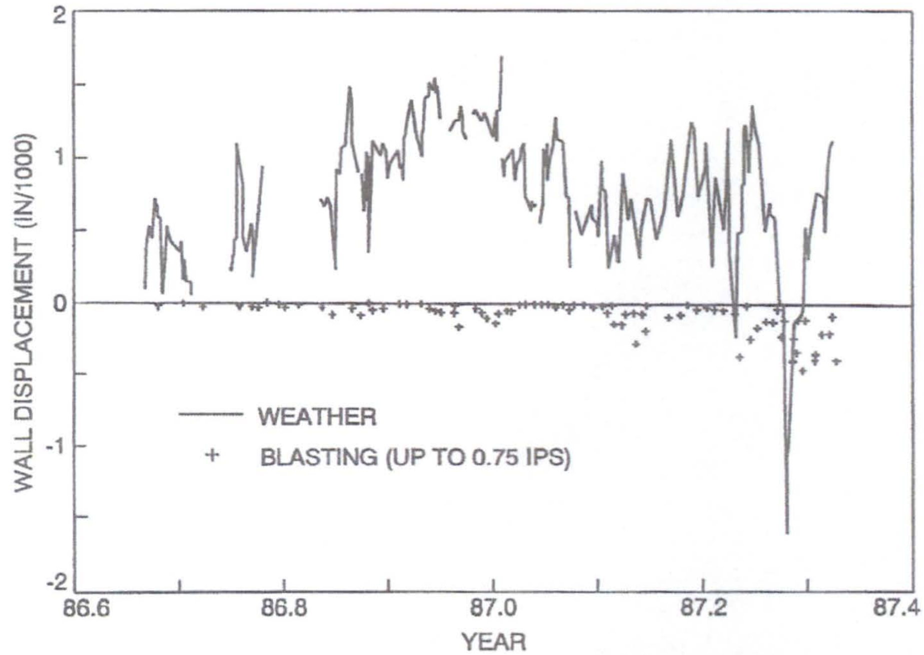
RI 8507[1] set a classification table for description of damage.

| CLASSIFICATION | DESCRIPTION OF DAMAGE |
|---|---|
| Threshold | Loosening of paint, small plaster cracks at joints between construction elements, and lengthening of old cracks. |
| Minor | Loosening and falling of plaster, cracks in masonry around openings near partitions, hairline to 1/8" cracks, and fall of loose mortar. |
| Major | Cracks of larger than 1/8" in walls, rupture of opening vaults, structural weakening, and fall of masonry. |

This same investigative report[1] states, "All homes are cracked from natural causes, including settlement and periodic changes of humidity, temperature, and wind. Soil moisture changes are notorious for causing foundation cracks. The widths of old cracks change seasonally and often daily; however, the number of cracks continues to increase with age, independent of

[1] Siskind, D., et al., "Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting," in USBM RI 8507, (1980), pp. 47, 49, 73

blasting." Dowding[2] documented this phenomenon by monitoring the interior crack at the joint of two sheets of drywall over time. (Figure 1) Blasts are measured against weather changes.




CRACK DISPLACEMENTS FROM WEATHER CHANGES AND BLASTING VIBRATIONS

**Figure 1**

The effect of natural environmental events on a structure has also been presented by Catherine Aimone-Martin and Charles Dowding at the 31st Annual Conference on Explosives and Blasting Technique (2005). Strain gauges placed on existing exterior cracks were monitored over time. Micro-inches of strain were measured and compared blasting events against temperature, humidity, normal household occurrences, etc. The monitoring revealed much higher levels of strain on existing cracks from natural events than blasting operations.

Another consultant and author on blast vibrations, Lewis Oriard[3], quotes, "If the regulatory limit or criterion designed around threshold damage is reached or exceeded moderately, it does not mean that damage will occur and in particular does not mean that major damage will occur, or even that minor damage will occur. It means only that there is an increasing probability of threshold damage." He also states, "By definition, threshold damage occurs in all houses independently of external vibration."

---

[2] Dowding, C., Construction Vibrations, Prentice-Hall (1996)
[3] Oriard, L., "The Effects of Vibrations and Environmental Forces", in International Society of Explosives Engineers, (1999), p.186

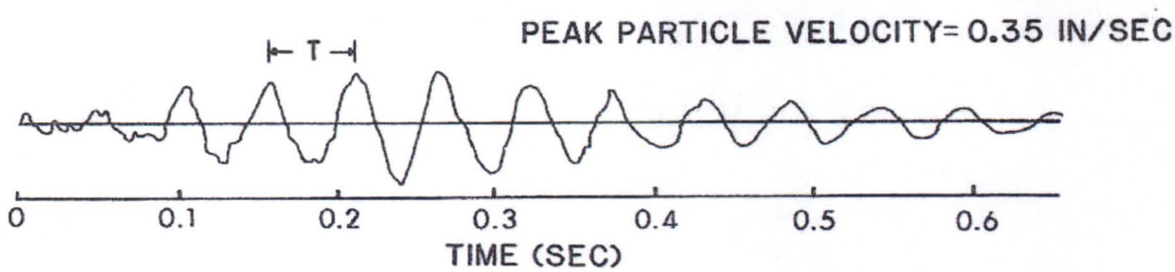
These well-respected researchers have documented blasting levels that may increase the potential for threshold, minor, and major damage. Damage, for the purposes of this report, will be considered only as threshold. This is demonstrated in over 500 investigations of blast damage by specialists at the Office of Explosives and Blasting (OEB) from June 2000 to present. Over 100 of these damage claims were forwarded to a claims adjuster and only two claims were found to have merit. Both of these claims would be considered threshold damage.

The function of this report is not to redefine ground vibration or airblast damage levels, but to compare particular compliance methods against others in the West Virginia coalfields and their ability to measure adverse effects on protected structures. Title 199-1-3.2.c. requires, "The blasting plan shall also contain an inspection and monitoring procedure to insure that all blasting operations are conducted to eliminate, to the maximum extent technically feasible, adverse impacts to the surrounding environment and surrounding occupied dwellings."

The four OSM monitoring methods are:

- Maximum Peak Particle Velocity
- Scaled Distance Equation
- Modified Scaled Distance
- Blasting Level Chart

An item to explain, for clarity of this report, is the concept of frequency. Frequency is described as ground vibrations measured in oscillations per second. The unit of measurement is called Hertz (Hz), which is one oscillation per second. Figure 2 is an example of a simple seismic wave and one method of frequency calculation.




PERIOD = T = 0.054 SEC

FREQUENCY = 1/T = 1/0.054 = 18 Hz

**Figure 2**

The above waveform frequency is calculated by using the Zero Crossing method. This calculation uses the distance in one cycle between the points when the waveform crosses the time-axis at the highest peak particle velocity (PPV). The frequency is described as 1/T where T is the time period. Although this method only calculates the frequency at the highest PPV obtained, it is most commonly used in seismograph printouts and the Blasting Level Chart. Frequency is also calculated over the duration of the seismic event and a predominant frequency can be found. This is described as FFT or Fast Fourier Transform. Response Spectra is a third method of frequency determination. This method considers "damping" which is the rate of response vibration decay after the ground vibration has ended. Future research that focuses on natural structural frequencies and response will use the response spectra calculation.

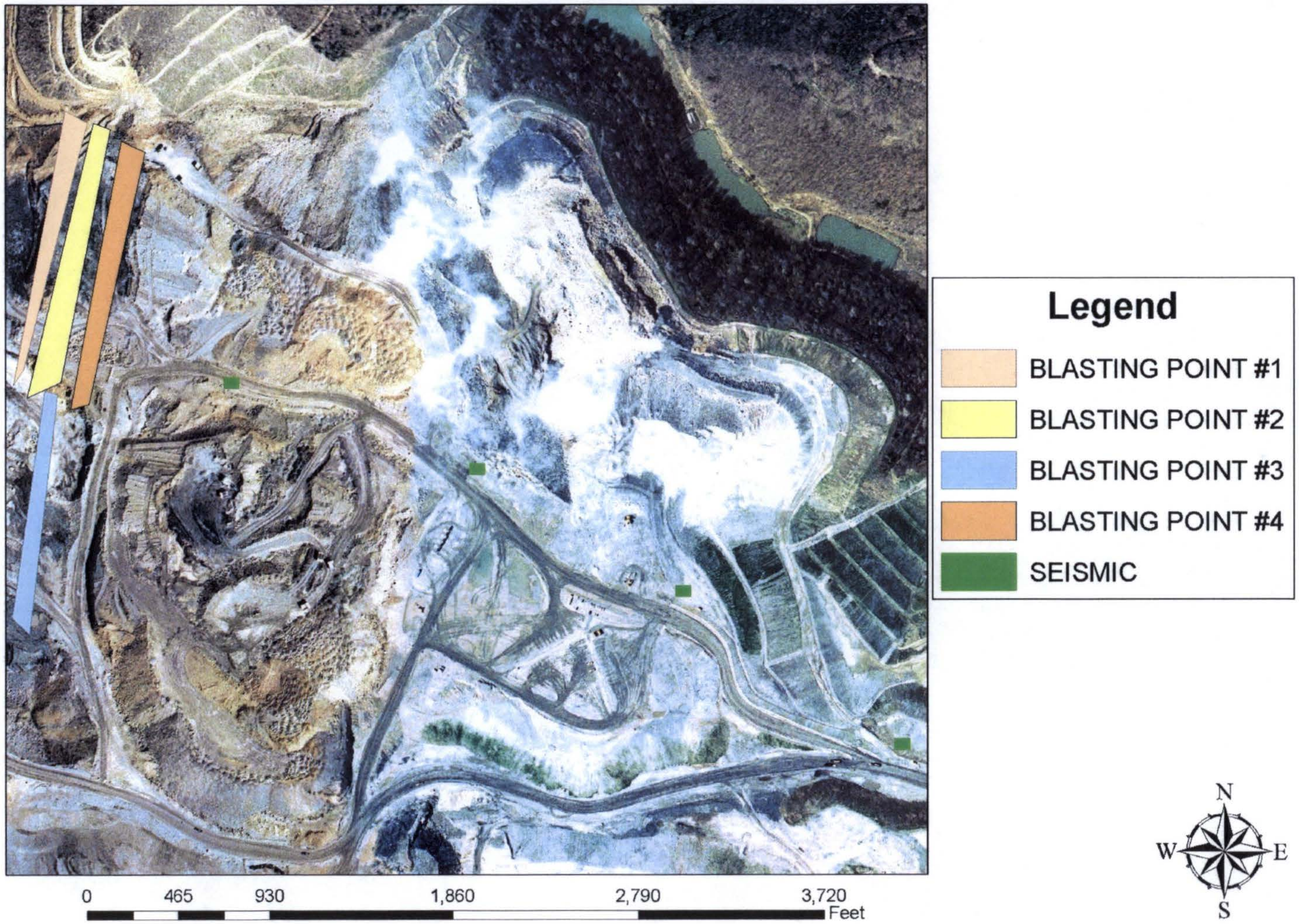
It is important to consider frequency as OSM's Blasting Guidance Manual[4] states that PPV, frequency, and blast duration are the "most appropriate and accurate indicator[s] of possible blast damage." Every structure has a natural frequency that can be excited by external sources such as blasting. When these two frequencies match, structural shaking occurs. Studies have determined that one to two story homes have a natural frequency range of 4 – 18 Hz. The only compliance method that utilizes frequency is the Blasting Level Chart.

## OEB COLLECTED FIELD DATA

OEB seismograph linear arrays have been regularly used over the last two years to collect information from various blasting research. This information originated from large cast blasts detonating over 2,000,000 pounds of explosives (40,000 pounds per delay) to smaller blasts of approximately 25,000 pounds (200 pounds per delay). Seismographs were placed at specific intervals behind blasts that ranged from 100 feet to 5,000 feet. Map 1 represents seismograph arrays in large casting operations, while Map 2 is arrays in closer proximity of structures and thus detonates less pounds per delay.

[4] Rosenthal, M. et. al, Blasting Guidance Manual, Office of Surface Mining, (1987) pp. 13, 30

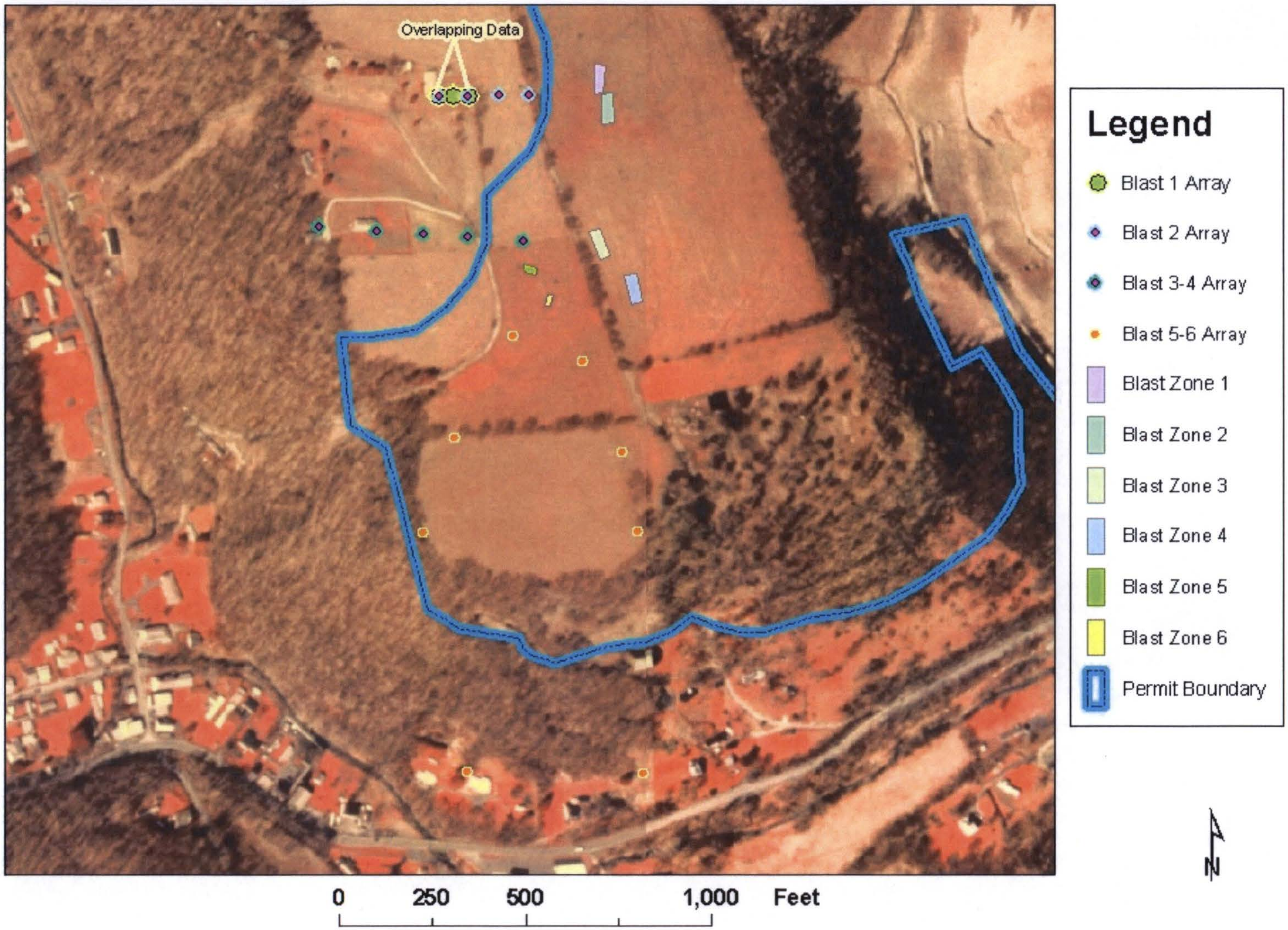
## SEISMIC ARRAY RESEARCH




Map 1

Map 2

**Seismic Array Research**
**2003**



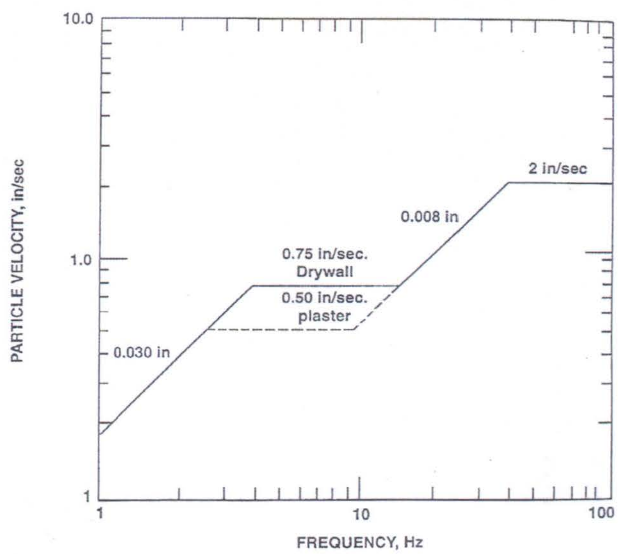
Information collected from these seismic arrays, GPS measurements, and blast logs used in this report includes PPV, frequency, distance, pounds per delay, and decibels. Most of this data is analyzed with OSM's Blast Log Evaluation Program (BLEP). The above mentioned blast log parameters are typed into the BLEP program and various graphs are produced for review. Three of the graphs used extensively in this report are Scaled Distance, PPV, and Blasting Level Chart (BLC).

## MAXIMUM PEAK PARTICLE VELOCITY VS. BLAST LEVEL CHART

These two compliance methods require seismograph monitoring. The maximum PPV allowed, which also minimizes the potential for threshold damage, is dependent upon the distance from the blast to the structure being monitored. This distance and corresponding maximum PPV allowed is defined as:

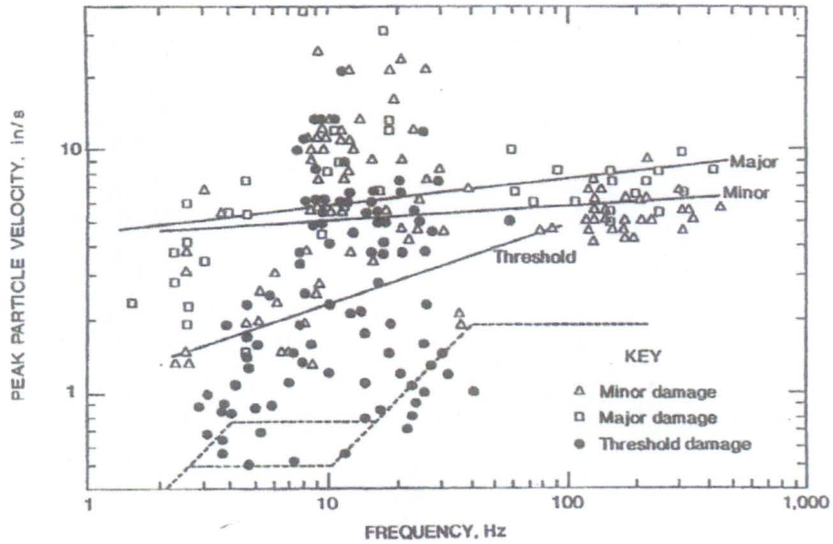
| DISTANCE (FT) | MAXIMUM PPV (IPS) |
|---|---|
| 0 – 300 | 1.25 |
| 301 – 5,000 | 1.00 |
| 5,001 + | 0.75 |

The Blasting Level Chart (BLC) considers not only PPV, but frequency as well, for threshold damage prevention. Graph 1 is the BLC from RI 8507 [1]. This alternate blast level criterion allows a ground vibration of 2.00 inches per second if the corresponding frequency is over 40 hertz. This graph does make a distinction between the potential for drywall and plaster damage. The USBM used a large data set to determine that plaster can withstand a 0.50 in/sec vibration level at lower frequencies (3 – 10 Hz), while OSM concluded drywall can endure up to 0.75 in/sec. at the same lower frequencies. Any points above the stepped line are considered non-compliant and may have an increased chance of damage to plaster or drywall. The BLEP program and OSM only recognizes the 0.75 in/sec PPV level of the graph.




**Graph 1**

A relationship between the BLC and threshold, minor, and major damage on a larger data set are represented in Graph 2[5]. It plots 718 blasts and 233 documented observations of cracks from RI 8507 and other independent studies and indicates that threshold damage does occur below 1.00 inches per second.

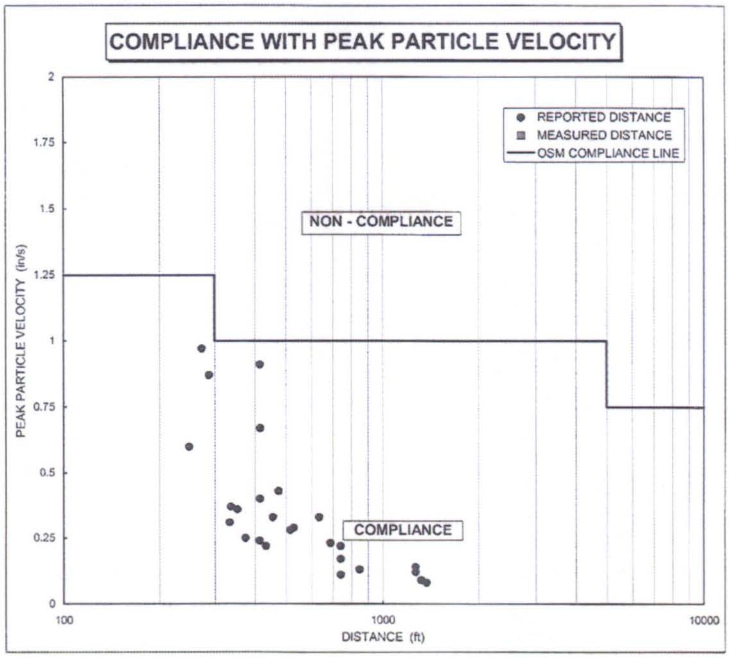



**Graph 2**

OEB research data was analyzed through BLEP to determine any differences between the Maximum PPV and BLC compliance methods. Data was separated into arrays used in northern and southern West Virginia coalfields. OEB seismographs that recorded ground vibrations less than 1.00 in/sec were specifically reviewed to see their position on the BLC because all research ground vibrations of greater than 1.00 in/sec were in the potential damage zone of the BLC.

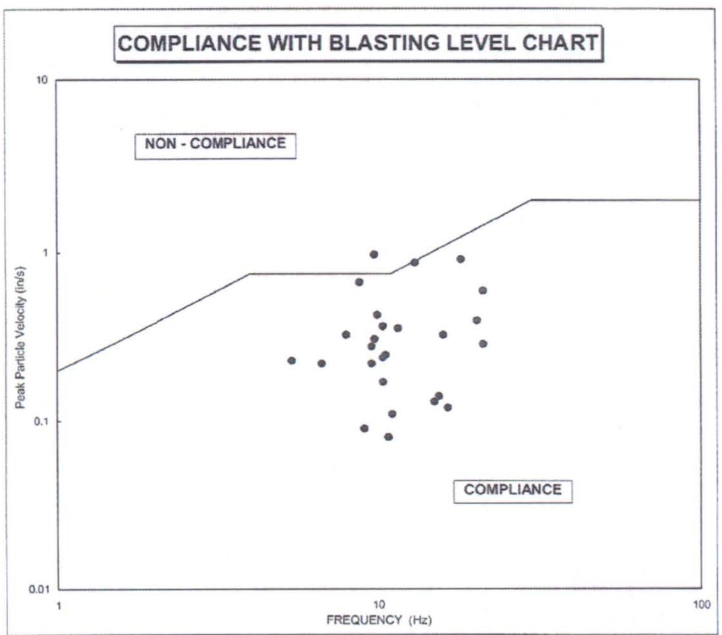
Twenty-six seismograph recordings from eight seismic arrays were entered into the BLEP program from small blasts in northern West Virginia. As stated before, only PPV values of 1.00 in/sec or less were analyzed. As expected, Graph 3 – Compliance with Peak Particle Velocity (PPV) reveals that all data sets were within the PPV compliance zone. This same data was plotted on the compliance with BLC indicated by Graph 4. One seismic record was positioned in the non-compliance zone for OSM's 0.75 in/sec level, while another record was in the USBM's non-compliance zone of 0.50 in/sec. Of the total recordings, these two points represent a non-compliance percentage of 4% on the OSM BLC.

[5] Siskind, D., "Vibrations from Blasting" International Society of Explosives Engineers (2000), p. 39




Notes: **Research Small Blasts - Northern WV**

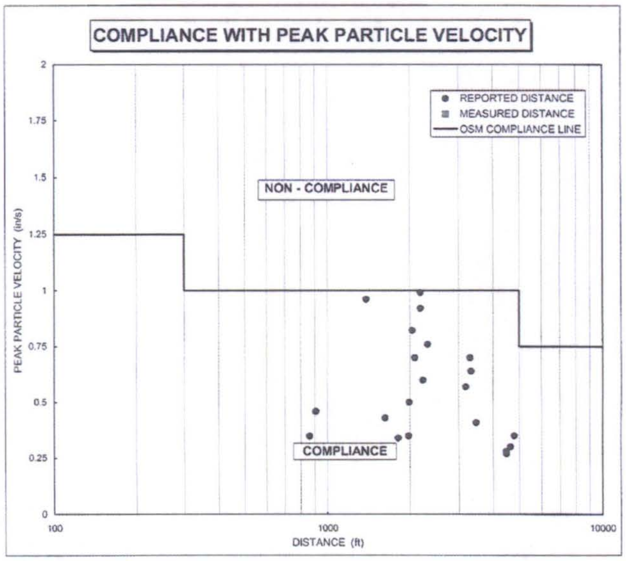
**Graph 3**




Notes: **Research Small Blasts - Northern WV**

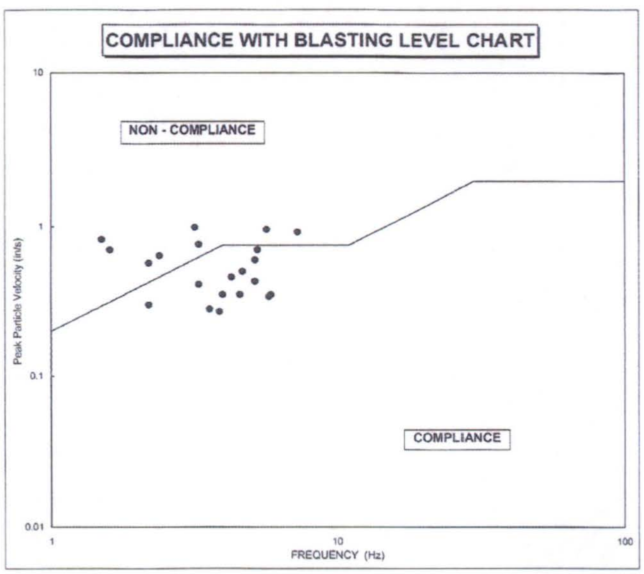
**Graph 4**

Twenty-one seismograph recordings from five seismic arrays also were entered into the BLEP program from larger cast blasts in southern West Virginia. In Graph 5, PPV again reveals that all data sets are in the compliance zone. This same data plotted on Graph 6, the BLC, shows eight records in the OSM non-compliance area while two more records are in the USBM non-compliance zone. This represents 38% of the data that is compliant with the maximum PPV, but non-compliant with the OSM BLC.




Notes: **Research Large Blasts - Southern WV**

**Graph 5**




Notes: **Research Large Blasts - Southern WV**

**Graph 6**

The question arises why there is such a difference between northern and southern West Virginia PPV compliance and BLC non-compliance. Frequencies vs. distance were analyzed from both seismic arrays. Table 1 compares average frequencies over distance between northern and southern West Virginia research arrays.

**TABLE 1 – Average Frequency vs. Distance**

| Distance from Blast (ft) | Northern WV Frequency (Hz) | Southern WV Frequency (Hz) |
|---|---|---|
| 0 - 500 | 15.6 | NA |
| 501 - 1000 | 12.6 | 6.1 |
| 1001 - 1500 | 11.2 | 6.2 |
| 1501 - 2000 | NA | 5.1 |
| 2001 - 2500 | NA | 3.9 |
| 2501 - 3000 | NA | NA |
| 3001 - 3500 | NA | 3.7 |
| 3500 + | NA | 3.7 |

This data reveals a difference between blast frequencies generated (501 ft to 1,500 ft) from the two areas of the state. RI 8507 explains that geology and blast delay intervals have a strong effect upon frequency characteristics. Although geologic cross sections were not analyzed for this report, all northern West Virginia blasts recorded had geophones placed in pre-mined ground, while most of the southern West Virginia blasts had geophones placed in stripped areas. Actual blast firing sequences would be difficult to determine from the northern West Virginia blast logs as the non-electric initiation systems utilized pyrotechnic delays. These burning delays have a 5 - 10% "scatter" from their nominal firing time. The southern West Virginia seismic data recorded blasts that used electronic digital detonators (EDD). Previous velocity of detonation (VOD) research from the authors has shown consistent delay firing times to within 0.1 milliseconds when using EDD. It has also been experienced by the authors that the use of EDD signature hole analysis using linear supposition (prediction), and modified blast delay firing times can manipulate blast frequencies out of a structure's natural frequency. This past research was conducted in aggregate scenarios where limestone geology was a favorable medium for this type of destructive interference. OEB has continually sought permits that consume electronic digital detonators as their initiation system for research.

At present, more array data is needed at longer distances in northern West Virginia to give a better comparison to southern frequencies. Additional research should also be collected on blast frequencies up to 300 ft from blasts. OSM's Blasting Guidance Manual states, "At close distances, up to 300 ft from a blast, high frequencies (above 40 Hz) predominate the vibration record. These higher frequencies are well above the fundamental natural frequencies of residential structure, so a higher particle velocity limit of 1.25 inch per second is allowed." OEB's preliminary data indicates average frequencies of less than 16 Hz. up to 500 ft from blasts.

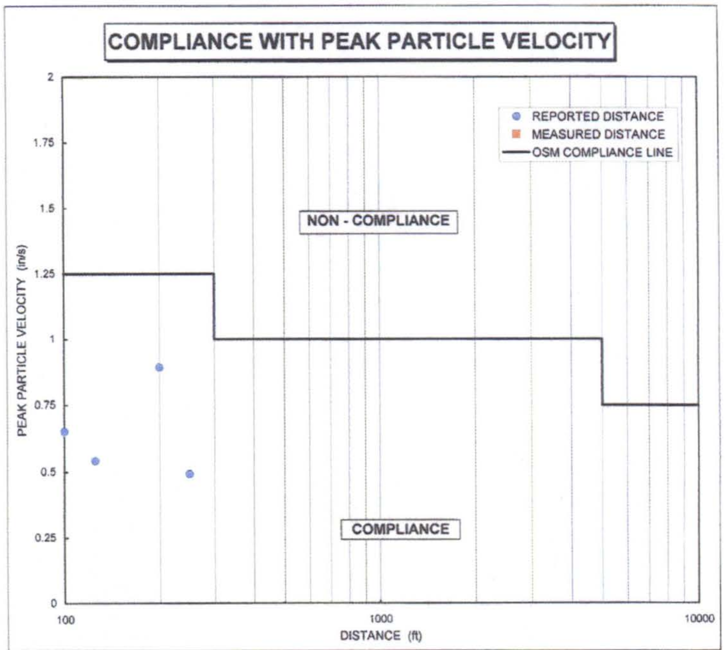
Damage claims in which the claims adjuster determined the blast damage claim had merit, were reviewed. The damage claim process involves an investigation by OEB specialists and a determination that the merit of the alleged blasting damage can be made or not made. This information is forwarded to the claims administrator who assigns the case to a claims adjuster. The adjuster will make a preliminary determination as to the merit of the blasting damage claim.

Claim A, in northern West Virginia, was determined to have blasting related cracks from pre-existent plaster damage and damaged window seals. Four blasts are particularly noted in the adjuster's report (Table 2).

**TABLE 2 – Damage Claim Blast Log Information**

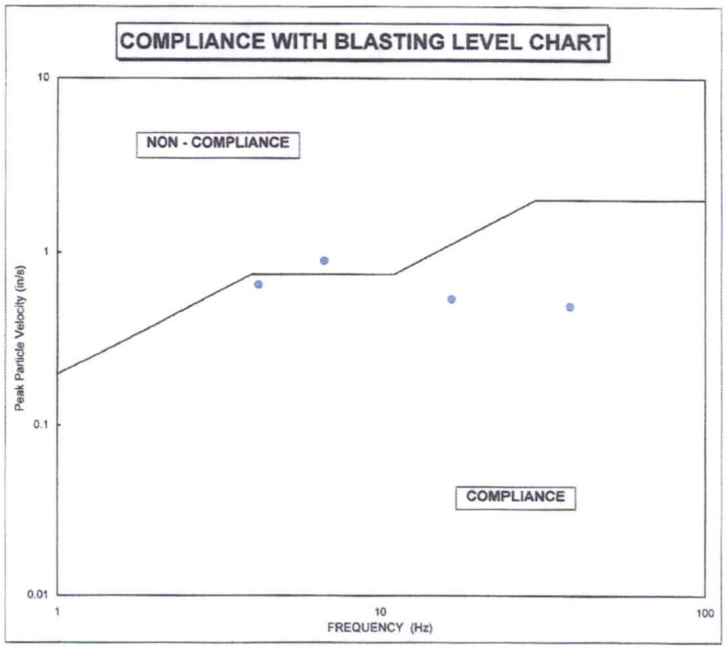
| Distance from Blast (ft) | Maximum PPV (in/sec) | Frequency (Hz) |
|---|---|---|
| 100 | 0.65 | 4.2 |
| 125 | 0.54 | 16.6 |
| 200 | 0.89 | 6.7 |
| 250 | 0.49 | 38.4 |

The claims adjuster states, "If the vibration levels generated by the closest blast … are plotted on the USBM chart (Graph 1), we find that vibration levels recorded at this structure could have generated damages at the site." Graph 7 and Graph 8 are the four blasts plotted onto BLEP's Compliance with PPV and Compliance with BLC respectively. The BLC clearly shows two blasts in the USBM non-compliant area of the graph, but within regulatory limits of the maximum PPV. The claims adjuster makes note of the fact that all blasting was compliant with the law and extensively used the pre-blast survey as part of his determination.




Notes: **Claim A - Northern WV**

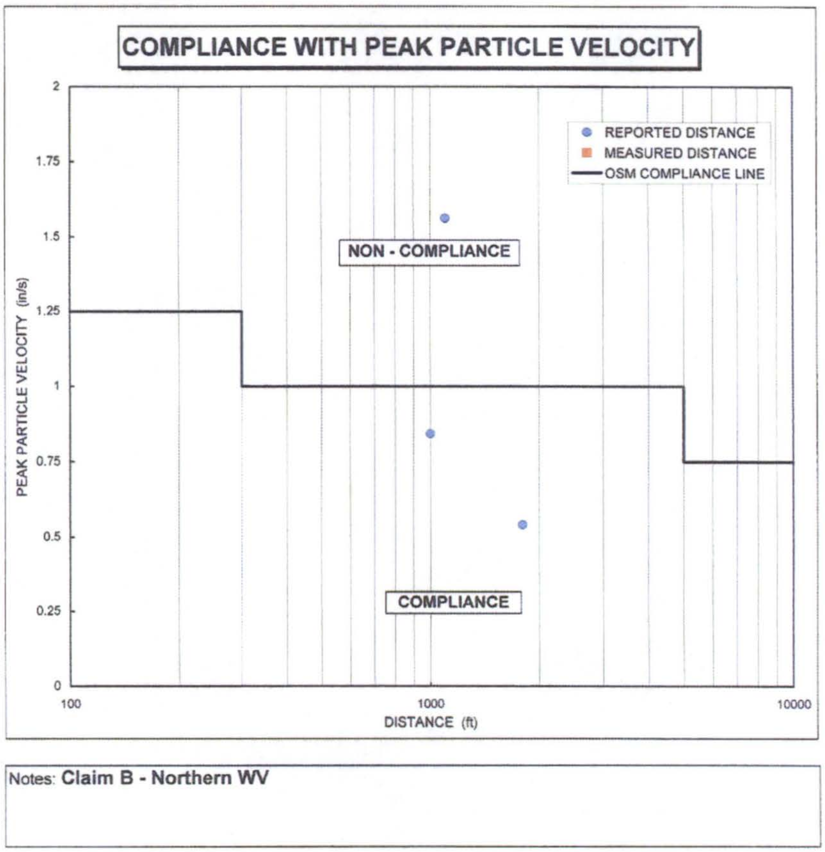
**Graph 7**



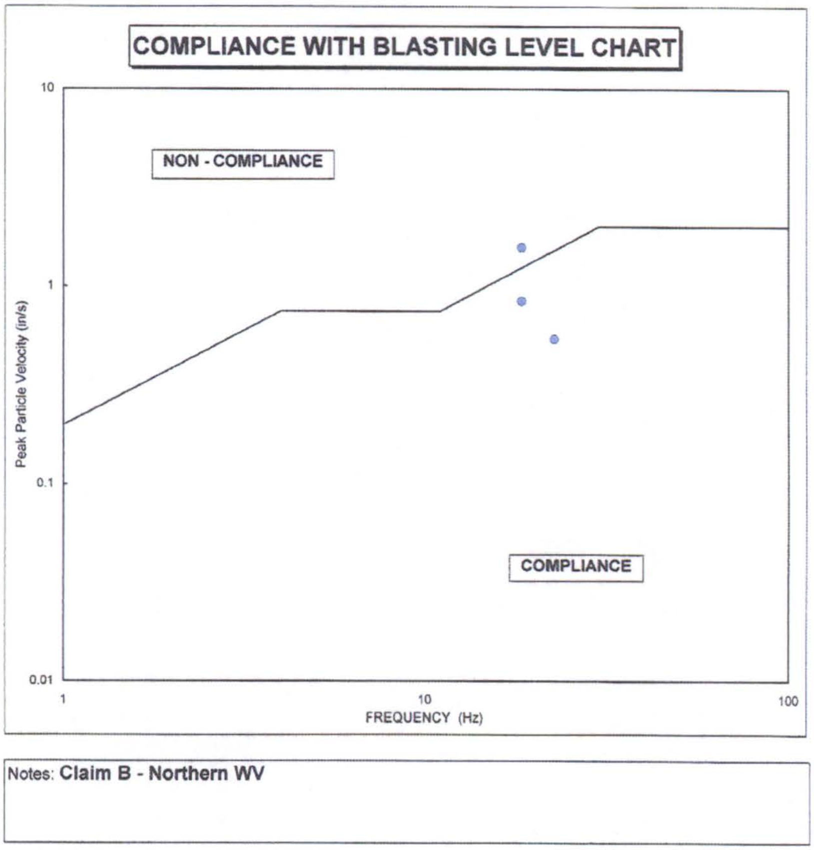

Notes: **Claim A - Northern WV**

**Graph 8**

Claim B, also in northern West Virginia, had various damages to a structure attributed to blasting. The damage included new blasting related cracks from pre-existing plaster damage, hairline cracks in six different locations, and four cracked marble sills. Exterior damages included hairline cracks in the stone façade. Again, it is noted that the claims adjustor used the pre-blast survey extensively in his determination of damage, but also noted, "Many of the vibrations striking the home during this period were of a low to medium frequency. Generally, frequencies within the 4 to 15 hertz range can present greater problems for structures than higher frequency vibrations. The number of low frequency vibrations striking this home may be a factor in damage development." Graph 9 (PPV) and Graph 10 (BLC) represent the three blasts that the adjustor believed were of significance in the damage determination. The BLC was referenced in the report. Although only one blast exceeded the maximum PPV and BLC, it is interesting to note that 11 different hairline cracks were attributed to one non-compliant blast.




**Graph 9**




**Graph 10**

A final OEB comparison between maximum PPV, Scaled Distance, and BLC revealed that blasts with a scaled distance of 41 or less and a PPV of 0.41 ips or higher may be in the BLC non-compliant area and may have increased potential for threshold damage to a structure. Array research and actual blast log information closely correlated on this issue.

## SCALED DISTANCE FORMULA AND AIRBLAST COMPLIANCE

The scaled distance formula is based upon numerous data sets collected across the United States from the USBM. This information was analyzed and regression analysis performed to determine ground vibration limits to prevent damage to structures. It is described as:

Scaled Distance ($D_S$) = $D / W^{0.5}$ where

D = Distance, in feet, from blast to structure
W = Maximum pounds per 8 millisecond delay

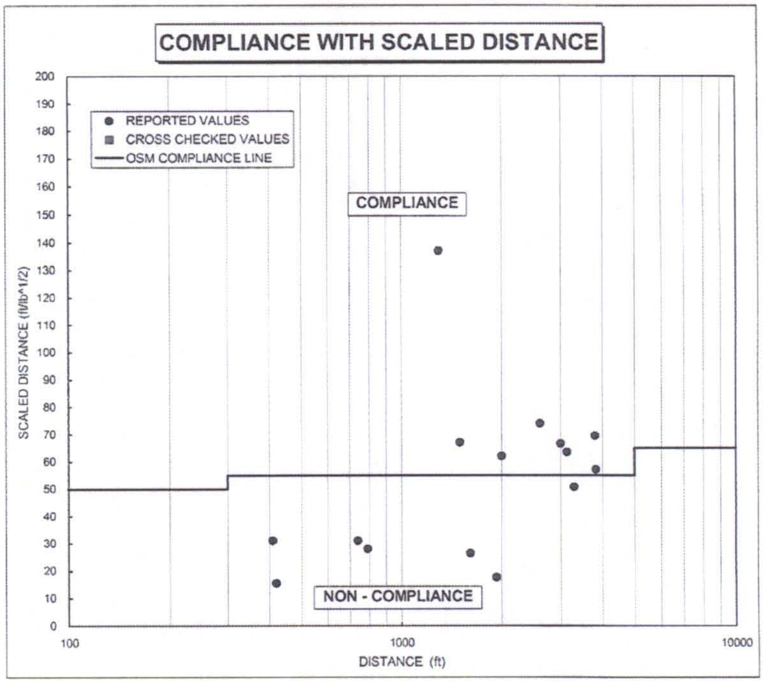
This formula sets minimum scaled distances at various distances. They are as follows:

| Distance (ft) | Minimum Scaled Distance |
|---|---|
| 0 – 300 | 50 |
| 301 – 5,000 | 55 |
| 5,001 + | 65 |

OEB array research determined that the small and large blasts easily maintain a 1.00 ips level at a scaled distance between 50 and 65. This demonstrates the relationship between maximum PPV and scaled distance.

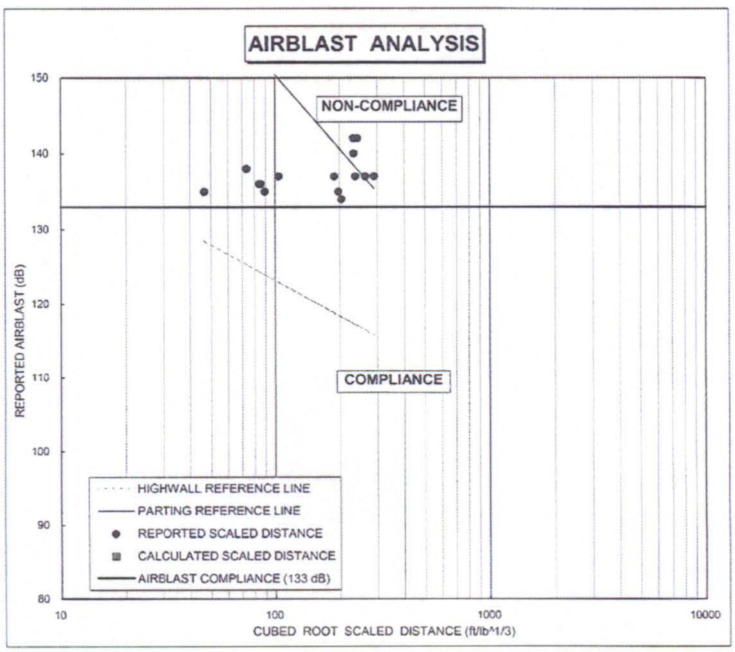
Although the scaled distance formula is used for ground vibration limits, it does not consider the 133 dB airblast compliance level. OSM's Blasting Guidance Manual states "There is general agreement among blast vibration experts, governmental regulatory and consultants, that the first damage due to airblast take the form of broken window glass." Siskind's research indicates that a 140 dB sound level is high enough for window and plaster threshold damage.

Airblast Notice of Violations (NOV) written by DMR and OEB inspectors/specialists over the past three years were reviewed. Although 20 airblast violations were written by DEP/OEB, only 15 violations with their corresponding blast logs and seismic waveforms could be retrieved or verified. Graph 11 plots Scaled Distance with respect to distance for the non-compliant airblast violations. This graph reveals that eight out of 15 violations had compliant scaled distances, but Graph 12 demonstrates that all the blasts were non-compliant with respect to airblast. **This data illustrates that 53% of airblast NOV's have a scaled distance of 55 or higher**. Of these airblast levels, three blasts had levels of 140 dB or higher. This represents 20% of all violations for airblast. Since 30 data sets were not obtained, this information must be considered a trend and not statistically valid. OEB will continue to track airblast violations and their corresponding scaled distances for future research and regulatory purposes.




Notes:**Research - Airblast**

**Graph 11**




Notes: **Research - Airblast**

**Graph 12**

OEB's particular research seismic arrays indicate scaled distances of 50 or greater resulted in airblast levels lower than 133 dB. It must also be noted, these arrays were placed behind the blasts which is favorable for worst-case PPV recordings, but not airblast measurements.

The NOV data would indicate that the scaled distance formula is not a particularly reliant method for airblast compliance. RI 8485 states that a minimum cube-root scaled distance of 180 $ft/lb^{.333}$ should be maintained when no seismograph monitoring is conducted on coal highwall. The following table reveals that 60% of the violations had a 180 $ft/lb^{.333}$ or higher value.

**TABLE 3. - Airblast Notice of Violations (2002-2005)**

| Decibels | Scaled Distance | Cube Root Scaled Distance | Blast Type |
|---|---|---|---|
| 137 | 67 | 238 | Production |
| 142 | 57 | 233 | Production |
| 140 | 64 | 234 | Production |
| 134 | 51 | 204 | Production |
| 138 | 31 | 74 | Production |
| 135 | 15 | 47 | Production |
| 136 | 28 | 86 | Production |
| 135 | 31 | 89 | Production |
| 137 | 67 | 189 | Binder |
| 137 | 137 | 291 | Binder |
| 136 | 18 | 84 | Production |
| 142 | 74 | 243 | Production |
| 135 | 62 | 198 | Production |
| 137 | 69 | 264 | Production |
| 137 | 26 | 104 | Production |

A regression analysis was attempted to determine the minimum cube-root scaled distance formula that would have kept the above non-compliance airblast levels within legal boundaries. The fact that there were not at least 30 data points and the "goodness of fit" was only a 0.14, no correlation could be made.

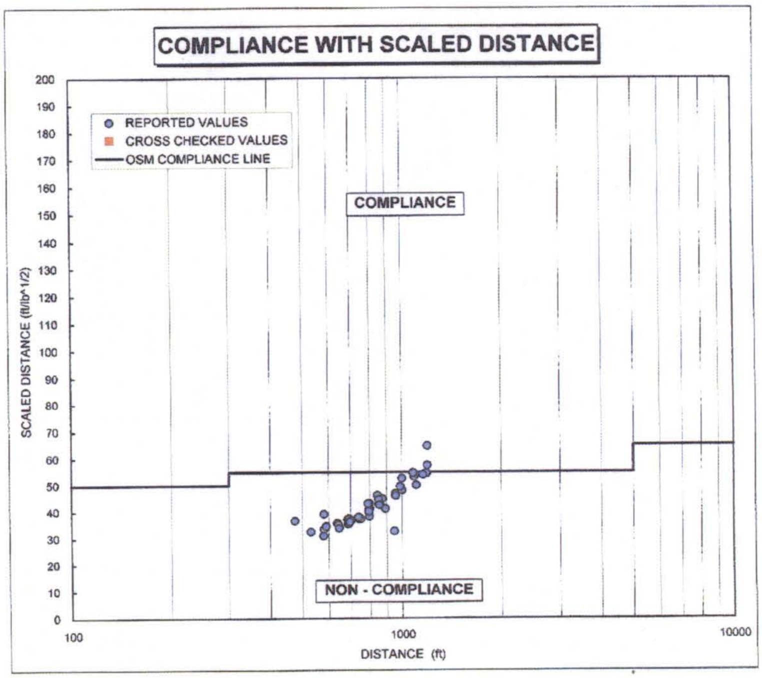
A review of the blast logs could find only one common factor for the non-compliant airblasts. Calculations revealed nine blasts that had delay sequences with shot velocities across the open free-face exceeding the speed of sound (1,100 ft/sec.). Other suspected causes include cracked geology around boreholes, depth-to-burden ratios of less than 1.0, and re-initiation of misfired explosives.

# MODIFIED SCALED DISTANCE

This compliance method uses a technique called least squares regression analysis. If enough data sets (PPV and scaled distance) are used, a ground vibration predictive equation is generated. Currently, there is only one permitee in West Virginia using this as their compliance method as stated in their permit blast plan. Their regression equation of $PPV = 242 * (D / W^{0.5})^{-1.60}$ dictates the maximum pounds per delay allowed for a given distance. The fact that they monitor all blasts helps to measure the success or failure of this type of compliance method. Fifty blasts were used in this analysis. Table 4 compares the modified Scaled Distance data against the other compliance methods.

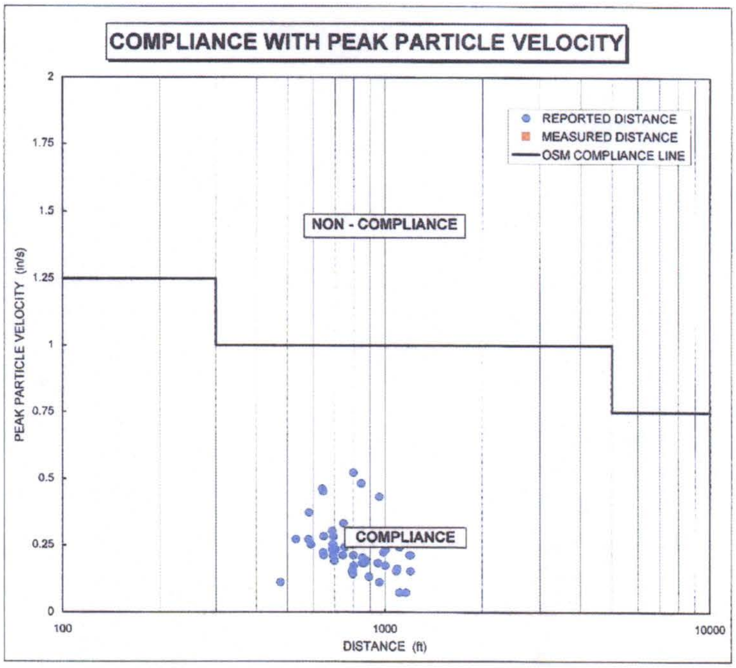
**TABLE 4 – Compliance Comparisons**

| Graph # | Compliance Graph Type | Result |
|---|---|---|
| 13 | Scaled Distance | Non-Compliant |
| 14 | Peak Particle Velocity | Compliant |
| 15 | Blasting Level Chart | Compliant |
| 16 | Airblast Analysis | Compliant |



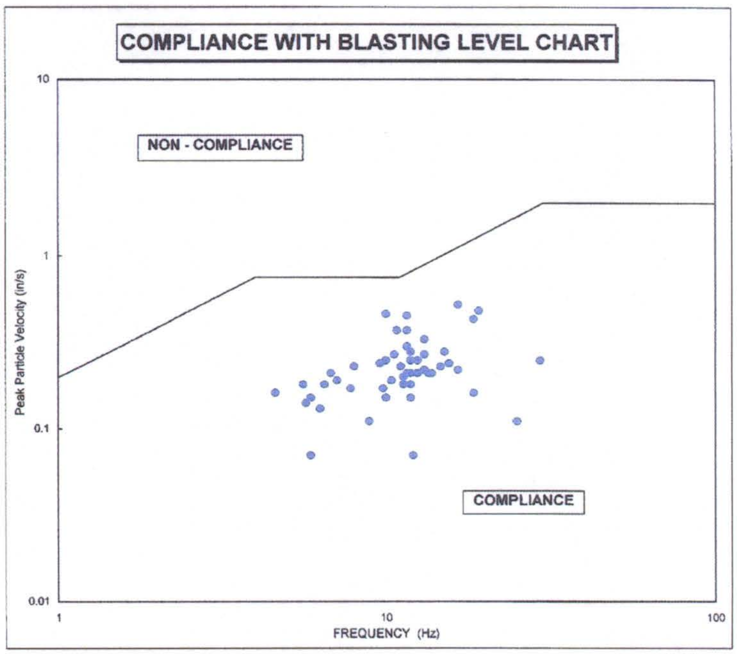

Notes: Research - Modified Scaled Distance
$PPV = 242 * (D / W^{.5})^{-1.6}$

**Graph 13**



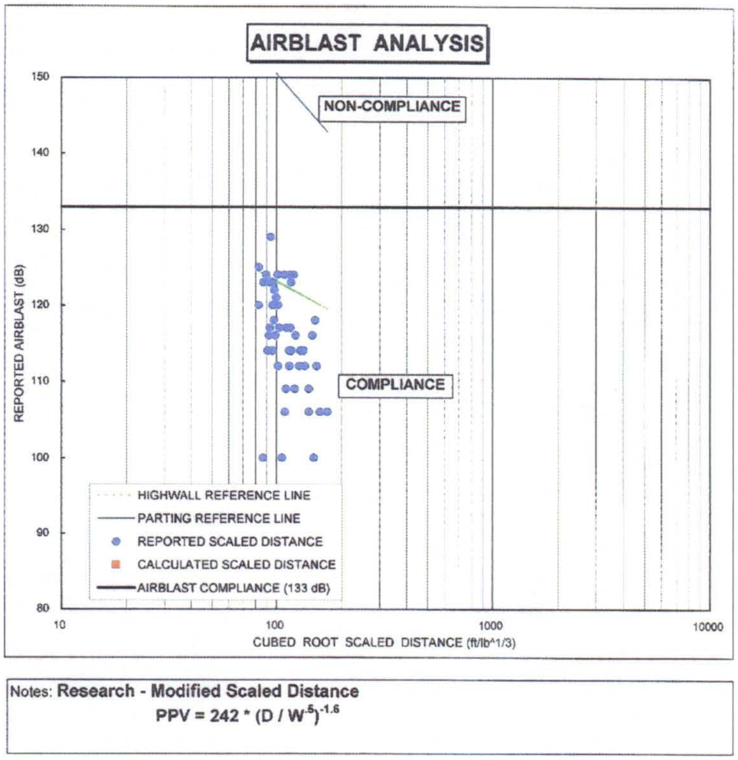

Notes: **Research - Modified Scaled Distance**
**$PPV = 242 * (D / W^{.5})^{-1.6}$**

**Graph 14**




Notes: **Research - Modified Scaled Distance**
**$PPV = 242 * (D / W^{.5})^{-1.60}$**

**Graph 15**




**Graph 16**

These graphs indicate that a majority of the reviewed blasts were non-compliant with scaled distance, but were well within legal limits when compared against PPV, BLC, and airblast levels . It should be recognized that these blasts were in close proximity to structures and a good blast design was properly executed in the field.

## CONCLUSIONS

This report concludes that although a small percentage of actual blast damage claims are actually threshold damage, there are differences between the various compliance methods detailed by OSM. Most notably is the comparison between the PPV and BLC. Field research, blast logs, and actual damage claim information was used to show compliance with PPV, but non-compliance and an increased potential for structure damage when compared to the BLC. A particular blast damage claim was awarded in the northern West Virginia coalfields although the investigated blasts were less than 1.00 in/sec. Frequencies for these blasts were generally very low, although the distances from the blasts never exceeded 250 ft. Governmental agencies and independent consultants agree that frequency has a great degree of influence on potential structure damage. OEB's study confirms this also. The compliance level of the BLC could assist in differentiating between blasting threshold damage and natural environmental effects such as humidity, temperature, normal household occurrences, etc… The importance of a good pre-blast survey is critical in determining the merit of blast damage claims.

Research on Scaled Distance revealed it does protect structures when used for minimizing ground vibrations and when compared against the BLC. OEB research and actual blast log data indicate that a scaled distance of 41 or less and a PPV of 0.41 ips or higher can be non-compliant on the BLC. Other OEB research indicates that scaled distance does not account for airblast. WVDEP and OEB Notice of Violations for airblast from 2002 to 2005, were analyzed and found that 53% of blasts were compliant with scaled distance, but non-compliant with OSM airblast levels of 133 db.

One case of Modified Scaled Distance was reviewed and found to be effective as a ground vibration and airblast compliance method when compared against other compliance methods. Although most of the reviewed blasts had non-compliant scaled distances, the PPV, BLC, and airblast levels showed compliance. The fact that the permitee seismographed all blasts while still using the modified scaled distance formula helped give this compliance method credibility.

Based upon the findings of this report, more research should focus on the following areas:

1) Frequency data in the 0 – 300 ft. distance from blasts. This would support or differ from OSM's conclusion that coalfield blast frequencies in this distance range are predominately high (over 40 hertz).
2) Frequency data in northern West Virginia when electronic digital initiation systems are utilized. Distances from 0 ft. to 4,000 ft. should be monitored.
3) Correlations between scaled distance and airblast, particularly air overpressures over 133 decibels.
4) Natural frequency response of structures, particularly modular structures with cinder block supports.

# BIBLIOGRAPHY

1) Report of Investigations 8507: "Structure Response and Damage produced by Ground Vibration from Surface Mine Blasting" 1980. D.Siskind, M. Stagg, J.Kopp, and C. Dowding. Page 47, 49, 73.

2) "Construction Vibrations": 1996. C. Dowding. Prentice-Hall

3) "The Effects of Vibrations and Environmental Forces": 1999. L. Oriard. Page 186. International Society of Explosives Engineers.

4) Office of Surface Mining "Blasting Guidance Manual": 1987. M. Rosenthal and G. Morlock. Page 13, 30.

5) "Vibrations from Blasting": 2000. D. Siskind. International Society of Explosives Engineers. Page 39.