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INVESTIGATION OF DAMAGE TO STRUCTURES IN THE McCUTCHANVILLE-DAYLIGHT AREA OF SOUTHWESTERN INDIANA

Volume 2 of 3

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US Department of Interior
Office of Surface Mining
Reclamation and Enforcement
Kenneth K. Eltschlager
Mining/Explosives Engineer
3 Parkway Center
Pittsburgh, PA 15220
Phone 412.937.2169
Fax 412.937.3012
Keltschl@osmre.gov

U.S. Department of the Interior

Office of Surface Mining Reclamation and Enforcement

Part III

Blast Design Effects on Ground Vibrations in McCutchanville and Daylight, Indiana from Blasting at the AMAX, Ayrshire Mine.

BLAST DESIGN EFFECTS on GROUND VIBRATIONS

in

McCUTCHANVILLE and DAYLIGHT, INDIANA

from

BLASTING AT THE AMAX, AYRSHIRE MINE

U.S. DEPARTMENT OF THE INTERIOR

OFFICE OF SURFACE MINING RECLAMATION AND ENFORCEMENT

EASTERN SUPPORT CENTER

10 PARKWAY CENTER

PITTSBURGH, PENNSYLVANIA 15220

KENNETH K. ELTSCHLAGER AND PETER R. MICHAEL

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INTRODUCTION

The Office of Surface Mining Reclamation and Enforcement (OSM), at the request of the Indiana Department of Natural Resources (IDNR), has been studying the effects of surface coal mine blasting on structures in the towns of Daylight and McCutchanville, Indiana, since 1989. The towns are located in the southwestern part of the state in Vanderburgh County near the City of Evansville, Indiana. Citizens began complaining to IDNR about blasting in mid-1988. Complaints ranged from annoyance to alleged structural damage.

The nearest mine to the complainants is the AMAX Coal Company's Ayrshire mine (Figure 1). Surface mine blasting has been used to fragment the rock overlying the No. 6 coalbed since mining began in 1973. The Ayrshire mine was included in numerous blasting studies since 1976 (3, 18, 23, 32). In 1988, the mine implemented a specialized form of blasting called cast blasting. Cast blasting not only fragments the rock but horizontally displaces the rock with explosive energy. The goal is to minimize the amount of rock that needs handling with equipment. To achieve this, larger quantities of explosives per unit volume of rock or a "higher powder factor" than with conventional blasting methods are used for each blast.

Three blast vibration impact related investigations were conducted between 1988 and 1992; the 1989 IDNR Two-Cut study (26), the 1990 U.S. Bureau of Mines (USBM) study (33) and this present Joint Investigation (JI) among the OSM, USBM, U.S. Army Corps of Engineers (COE) and U.S. Geological Survey (USGS). Complaint information obtained from the IDNR study and a 1989 OSM field survey was used to focus the evaluation of surface mine blasting activity. Many residents noted specific dates and times when blasting was felt at their homes. This allowed OSM to compare complaints with actual blasting at other area mines as well as the Ayrshire mine. These studies and Ayrshire mine blast logs from January 1, 1986, to April 15, 1992, were analyzed for the following purposes:

(1) determine the mine or mines responsible for the majority of complaints;

(2) develop a historical perspective of blasting at the Ayrshire mine in terms of total explosive weight per blast and the explosive weight per delay per blast;

(3) document the progression of the mine;

(4) identify the location and type of blast patterns used at the mine from January 1988 to April 1992;

(5) determine if blast patterns representative of those used during damage claim periods were the same as or similar to those monitored during the three studies; and

(6) based on blast patterns, develop a worst-case scenario for ground vibration amplitudes in Daylight and McCutchanville, Indiana.

DATA SOURCES

Data for this study were obtained from AMAX blast logs (January 1, 1986 to April 15, 1992), IDNR or OSM complaint logs (January 1, 1988 to June 15, 1989), IDNR and AMAX seismic monitoring (December 5, 1988 to February 27, 1989) and the USBM 1990 study (November 1, 1989 to January 3, 1989). Blast-log data included the date, time, coordinates, average depth of holes, total explosive weight, explosive weight per 8-millisecond delay, number of holes, minimum burden, minimum spacing, pattern type, seismic compliance station location, blast-to-seismograph distance, and seismic peak particle-velocity. Complaint data were correlated to Ayrshire blasts. A complaint is considered attributable to an Ayrshire blast if noted within +/- 15 minutes of the time recorded on the blasting log. This method was first used in the IDNR study. Finally, a regression analysis was performed on the IDNR study seismic data. Paradox, Reflex and Statgraphics, database and statistical software packages with graphical capabilities, were used to evaluate the data.

COMPLAINTS AND REGIONAL MINING ACTIVITY

Blasting damage claims and annoyance complaints received by IDNR escalated in 1988. With 23 other surface mines in the region (Figure 1), the possibility existed that more than one mine's activity was the direct or indirect cause of blasting related complaints. To address this concern, OSM compared the complaint dates and times with actual blast times for 1988 at Ayrshire. OSM compiled data from the IDNR study at the OSM field survey. The number of complaints per blast started to significantly increase in September 1988, as shown in figure 2. A strong increase in complaints during November 1988 is partly attributed to heightened public awareness during the publicized IDNR study.

In 1988 complaints were lodged for 187 of 528 blasts. Of 735 complaints, 602 (82%) were attributable to Ayrshire blasts. The remaining 133 complaints did not match blast times at Ayrshire. Furthermore, none of them occurred within +/- 15 minutes of each other. This lack of correlation indicates that there is no other significant source (i.e. another mine, earthquake, airport, etc.) responsible for generating complaints.

As a result, the rest of this analysis focused on the Ayrshire mine blasts.

The IDNR study (26) found that 64% of the complaints between September 1, 1988 and May 31, 1989, were tied to Ayrshire blasts and some complaints were attributable to other area mines. The increased correlation of incidence to Ayrshire mine blasts in the OSM analysis may be attributable to additional data obtained during the OSM field survey and interaction among the complainants (i.e. networking).

HISTORY OF BLASTING

Figure 3 shows the blast locations at the Ayrshire mine from January 1988 to April 1992 and the monitoring stations relative to Daylight and McCutchanville. The mine pit is in excess of three miles long and until 1991 moved westward by approximately one cut of the highwall per month or about 1/4-mile per year. During 1992 the mine reached the western boundary and began mining to the north.

Figure 4 demonstrates the general trend in blasting at the Ayrshire mine from January 1986 to April 1992 in terms of total weight of explosives per blast (total explosives). The graph shows that the size of blasts generally remained the same during 1986 and 1987, with no blasts exceeding 100,000 pounds. In 1988 and 1989 the size of blasts began to vary significantly and ultimately peaked at over 400,000 pounds. The largest blasts occurred in September-October 1989, just prior to the USBM study in November-December 1989. From 1990 through completion of the study (1992) the trend was toward using less explosives per blast.

Many factors influence ground vibration amplitudes including geological conditions, types of explosives, amount of explosives, blast hole layout, detonation sequence of the holes and errors in blasting caps. Blasting research (15, 23, 30) to date indicates that the best predictor of ground vibration amplitudes at some distance from a blast is the weight of explosives (explosives) detonated at any one time (delay). The explosives per delay for the purpose of this investigation is equivalent to the maximum explosives detonated within any 8-millisecond period as reported on the Ayrshire blast logs. At the Ayrshire mine, this is generally equivalent to the explosives detonated in one blast hole. A few blasts had decks of more than one charge per hole. In any blast, the amount of explosives per hole varied with hole depth. Figure 5 illustrates the explosives per delay used in each blast from 1986 through 1992. In 1986 and 1987 the explosives per delay rarely exceeded 2,000 pounds. As with the total explosives, the explosives per delay in 1988 and 1989 significantly increased over previous years and peaked at 8,500 pounds. The trend after 1989 was towards less explosives per delay. Table 1 summarizes Figures 4 and 5.

Table 1. Blasts January 1986 through April 15, 1992.

Year	Average Blasts per Month	Maximum Total Explosives (lbs)	Maximum Explosives per Delay (lbs)
1986	79	87,200	3,100
1987	57	79,750	2,700
1988	44	308,700	7,200
1989	24	411,688	8,500
1990	28	283,986	6,880
1991	29	160,425	3,380
1992*	30	93,780	1,800

(* 3.5 months)

The two blasting patterns generally used during 1986 and 1987 were in use since the early 1980's and are documented in USBM RI 8896 (35), RI 9026 (23), and RI 9226 (3). Blasting techniques used during the first two months of 1988 were identical to those used during 1986 and 1987. In February 1988, cast blasting began in the northern two-thirds of the mine and conventional blasting continued in the southern most area. Blast patterns are discussed in detail in a later section of this report.

COMPLAINT TRENDS

A preliminary complaint trend analysis was conducted in a relational database for the period corresponding with the IDNR study, December 5, 1988, to February 28, 1989. Complaints obtained by OSM and IDNR were included in the analysis. The period contained 81 blasts and 586 complaints. Of those, 502 complaints are attributable to Ayrshire blasts.

Fourteen elements were considered as potential influences on the number of complaints for each blast: total weight of explosives, maximum weight of explosives detonated per delay, blast duration, blast hole depth, average explosive weight per millisecond, powder factor, atmospheric pressure, temperature, wind direction, wind speed, humidity, sky cover, opaque cloud cover and precipitation. The degree of correlation between each element and number of complaints with ± 15 minutes of a given blast is presented Table 2. Correlations are considered significant when their absolute values are equal to or greater than 0.70.

Table 2. Spearman Rank Correlations between complaints and various mine blasting and weather parameters.

Parameter	Correlation
Total weight of explosives	0.8300
Weight of explosives per delay	0.7852
Blast duration	0.5720
Blast hole depth	0.4446
Average explosive weight per millisecond	0.5209
Powder factor	0.6317
Atmospheric pressure	-0.1577
Temperature	0.0496
Wind direction	-0.2759
Wind speed	-0.3583
Humidity	0.1884
Sky cover	0.1726
Opaque cloud cover	0.2262
Precipitation (previous day)	0.3050

Among these elements, total explosives followed by explosives per delay have the strongest statistical relationships to number of complaints during the IDNR study period. Other elements pertaining to blasting techniques also have significant correlations which may, however, be connected to the influence of total explosives. Elements representing weather conditions and ground moisture have low relationships by comparison. Among these, wind speed (which is independent of wind direction), wind direction, and barometric pressure show stronger relationships with the number of complaints. Figure 6 is a scatter plot showing the linear relationship between total explosives and number of complaints. Figure 7 is the same plot for explosives per delay.

BLAST DESIGNS

Rock fragmentation and ground vibrations are influenced by the blast powder factor, the geometry of the blast holes, the degree of explosive confinement and detonation sequence of the holes (1, 15). As these blast design characteristics are altered, the rock can be fractured in place (conventional blast) or it can be fractured and horizontally displaced (cast blast). Specialized conventional blasting applications include highwall smoothing (pre-split blast), initial blasts on new highwall cuts (box-cut blast) and breaking thin rock units between coal seams (parting blast). OSM classified blasts between January 1, 1988 and April 15, 1992 by design. Relationships were sought between blast design and ground vibrations to account for design influences and to develop a worst-case ground vibration amplitude scenario in McCutchanville and Daylight. Blast designs were also evaluated to determine how they correlated to complaints from January 1988 to June 1989. Characterization of the blasts are essential to compare blasts during the initial damage claim period (1988) and blasts during the IDNR, USBM and JI studies. The variety of blast designs employed are illustrated in Figures 8 and 9. Pre-split, box-cut and parting patterns are not shown because they generated few complaints as discussed later.

The weight of explosives per cubic yard of material blasted (lbs/yd^3), known as the powder factor, is a primary indicator of the blasting method and relates to the degree of explosive confinement. At the Ayrshire mine, conventional blasts typically have a powder factor less than 0.70 lb/yd^3 while cast blasts are typically over 1.0 lb/yd^3. When more explosives are used per unit volume of rock, the excess energy is consumed by displacing, in addition to breaking the rock. Pattern layout and detonation sequence of the blast holes helped distinguish the pre-split, box-cut and parting blasts. The blast patterns are defined as follows:

100 series - Conventional Blast Pattern
200 series - Cast Blast Pattern
300 series - Pre-split Blast Pattern
400 series - Box-cut Blast Pattern
500 series - Parting Blast Pattern

The tens value differentiates patterns within the series based on blast hole layout (rectangular or staggered) and blast initiation sequence (delay intervals between rows and columns). A 0 pattern represents miscellaneous or trial patterns that were infrequently used. Included in the 0 pattern are partial patterns detonated after being cut-off from the main blast (misfired blasts). The units value represents the dominant number of explosive decks per hole per blast (i.e. many blasts have both single and double decked holes). For example, blast pattern 212 is a cast blast with a powder factor > 1.0 lb/yd^3 (<u>2</u>00 series), with a staggered blast hole pattern delayed 17 millisecond(ms) between holes in a row and 200 ms between rows (2<u>1</u>0 pattern) and with blast holes that primarily have two decks (21<u>2</u> pattern type).

Figure 10 shows the spacial distribution of conventional, cast, pre-split, box-cut and parting blasts. The easting scale is exaggerated to enhance resolution of the pattern types. Conventional and cast blasts occurred in the southern and northern pit areas respectively. Pre-split blasts occurred much less frequently, and were widely distributed. Box-cut blasts also occurred less frequently, but were mostly confined to northern pit areas as the mine expanded in that direction. Parting blasts began in 1991. Areas void of blasting are attributable to a cemetery reservation and shallow unconsolidated overburden where blasting was not necessary for mining. Figures 11, 12 and 13 show the blast locations during the IDNR, USBM and

JI studies, respectively. Also shown on each are the AMAX ground vibration monitoring stations (compliance stations). All three studies included monitoring of conventional and cast blasts.

Table 3 illustrates the number of complaints per blast pattern series except for parting blasts (which were not used until 1991).

Table 3, Blast Pattern Series and Complaints

Blast Pattern Series	Blasts 1988	Complaints 1988	Blasts 1989*	Complaints 1989*
100	250	85	26	46
200	237	506	105	561
300	21	2	8	8
400	20	9	3	6
Total	528	602	142	621

* January 1989 to June 1989

Almost 5 out of 6 complaints in 1988 are attributable to cast blasts which represent nearly 45 percent of all blasts. Figures 14 and 15 summarize the average number of complaints per pattern from January 1988 through June 1989. In general, cast blast patterns resulted in significantly more complaints per blast than conventional patterns. Complaint data for patterns 260, 270 and 280 were not available because they were used after June 1989. Since conventional, pre-split and box-cut blasts had little influence on the number of complaints, further investigation focused on cast blasts. The most frequently felt blasts in terms of average complaints per blast were patterns 220, 230, and 240. A large number of complaints were also generated from the 200 or trial patterns. The complaints do not correlate with the number of decks used in a cast blast.

Figure 16 illustrates the time period of use for each conventional and cast blast pattern. Cast blast patterns used during the different study periods were; 220 and 230 during the IDNR study; 250, 260 and 270 during the USBM study; and 260, 270 and 280 during the JI study. Blast designs 210 and 240 were not monitored during any of the study periods. Pattern 210 was used in the summer of 1988 when the first structure damages were alleged to have occurred and just before an increase in number of complaints per blast. Pattern 240 was not extensively used. Pattern 250 was used frequently in the summer 1989 during which time effects of blasts were alleged to be most noticeable.

Cast blast patterns can also be described in terms of energy release. Each pattern is detonated one hole or deck at a time to minimize vibrations. The detonation sequence of holes in a pattern affects the pulses of energy released into the environment. Energy release diagrams for the standard cast blast patterns are shown in Figure 17. Patterns 210 through 250 are initiated row-by-row. They exhibit well defined, repetitive periods of energy release, each lasting approximately 1 second. Pauses in detonations between rows cause energy pulses to occur either 4 or 5 times per blast depending on the number of rows. The energy is imparted to the environment in 4 or 5 cycles per second. Pattern 260 and 270 are end initiated echelon designs where detonation sequencing forms a line oblique to the highwall. They exhibit integrated detonation times. These cast patterns were almost exclusively used during 1990 and 1991. Energy release during detonation is significantly different than in earlier patterns. The pattern begins with well separated detonations that become close together near the center of the blasts and then taper off to more well separated detonations at the end. In other words, detonations start slowly, culminate in a flurry of activity, and finally return to a slow end. This may have resulted in greater destructive wave interference and subsequently less vibrations. These patterns also resulted in few misfires or other problems as evidenced by Figure 16 where fewer 200 series blasts occurred during 1990 and 1991 than in 1988 and 1989.

BLAST PATTERNS AND GROUND VIBRATIONS

USBM RI 9226 (32) published the results of monitored vibrations at the Ayrshire mine during 1987, prior to the initiation of cast blasting. The expected or mean propagation of vibrations was described by the equation:

$$PPV = 51(SD)^{-1.16}$$

Where PPV is the peak particle velocity (inches per second) and SD is the square root scaled distance (feet/weight per delay$^{1/2}$). Patterns 110 and 120 were in use at this time.

The IDNR conducted the next study in the vicinity of Ayrshire. This study resulted the most comprehensive seismic database available for statistical analysis of ground vibrations. Vibration data were reported for up to ten locations per blast (total 75 blasts) at scaled distances ranging from 30 to 1000 ft/lb$^{1/2}$. Conventional, cast and box-cut blasts are included in the statistical analysis. The analysis included 211 data pairs (scaled distance, peak particle velocity). However, data pairs for 30 blasts at station 14 were excluded because of its spoil side location. Blast pattern 230 was primarily in use during the IDNR study (41 of 75 blasts). Regression analysis describes expected or mean ground vibrations by the equation:

$$PPV = 55\ (SD)^{-1.19} \qquad (R^2 = 73\%)$$

This equation is nearly identical to the RI 9226 equation. Therefore, the propagation of vibrations as described by two separate studies with distinctly different blast patterns yield same result. Two standard deviations from the mean yields the equation:

$$PPV = 137\ (SD)^{-1.19}$$

Figure 18 shows peak particle velocity data obtained during both the IDNR and USBM studies plotted with the mean and 95% confidence lines of the IDNR data. These two reference lines are used to compare the effects of the various cast blast patterns and develop a worst-case vibration amplitude for McCutchanville and Daylight. Most of the IDNR data is below the 95% confidence line. Three points exist above the line with scaled distances greater than 300 and peak particle velocities less than 0.20 in/s.

The USBM study (33) recorded peak particle velocities that fall below the mean line of figure 18 except for one. The study measured ground vibrations of seven structures; four in McCutchanville, two in Daylight and one along Baseline road. Blasts were generally recorded at larger scaled distances than the IDNR study. However when the scaled distances were the similar, the USBM data consistently showed lower peak particle velocities than the IDNR study. In other words, at comparable scaled distances, vibrations were higher during the IDNR study. This may be attributable to changes in blast design as discussed later.

Figure 19 represents all vibration data at the compliance station of each blast as recorded on Ayrshire blast logs from January 1986 to April 1992. This includes all conventional, cast, box-cut, pre-split and parting blasts. The graph shows a wide scatter of data points with some particle velocities exceeding the 95% confidence line and some exceeding 1.0 in/s at scaled distances less than 60 $ft/lb^{1/2}$. Little data exist below 0.1 in\s because it was the normally the trigger level of most AMAX seismographs.

Compliance stations (figure 3) are located either in front or behind active mining areas. In 1986 and 1987 AMAX mined around the Zoar Church (station 14). The church now sits on a block of unmined ground completely surrounded by reclaimed mine spoil. The church remained the primary monitoring location during much of 1988 and 1989 while east of the active mining areas.

Earlier we determined that the cast blasts yielded more complaints. Now we will show which patterns yielded higher

FIGURE 10

BLAST LOCATION BY PATTERN SERIES

(Easting scale exaggerated)

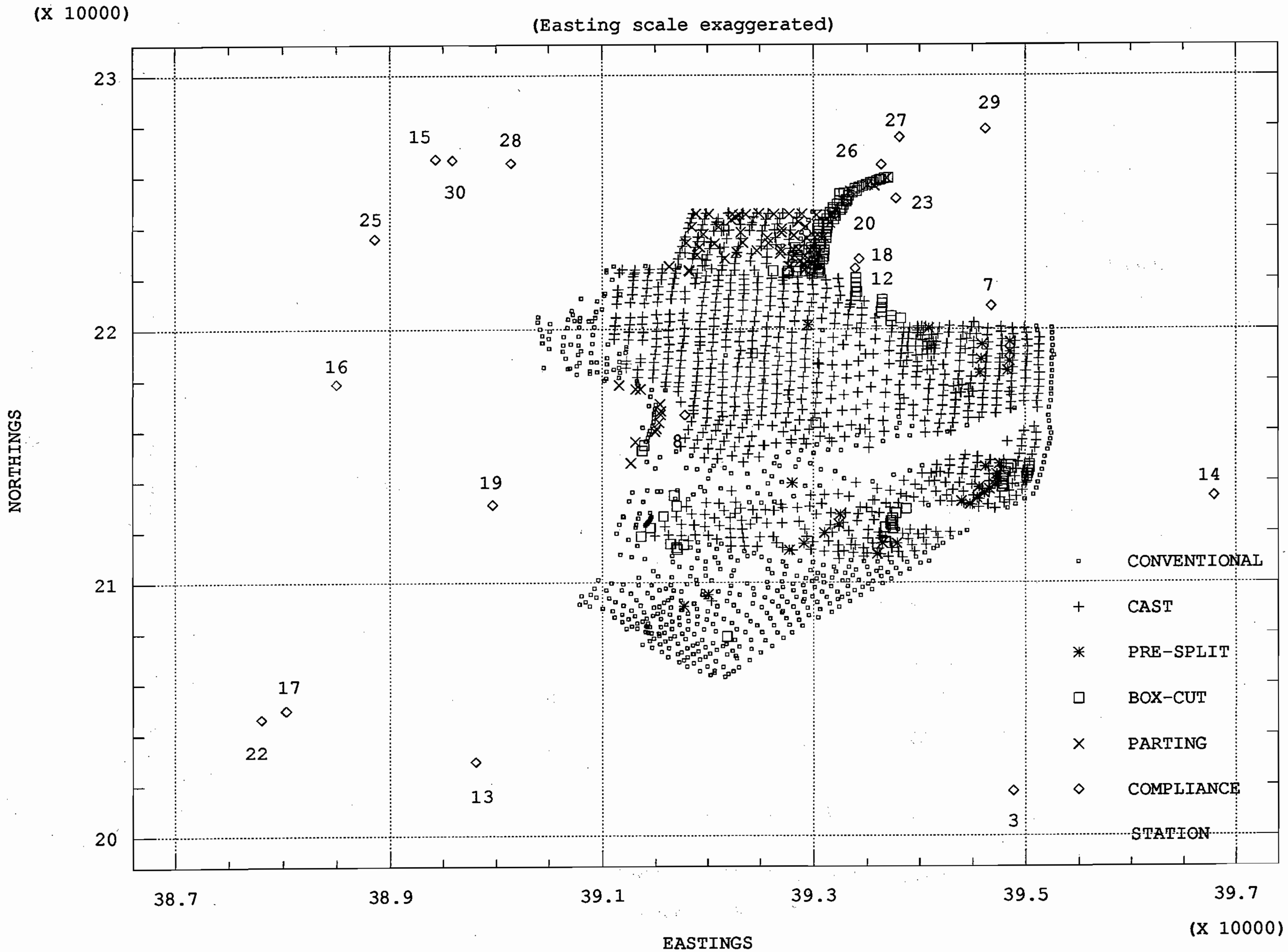


Figure 9 (cont.)
Cast Blast Patterns

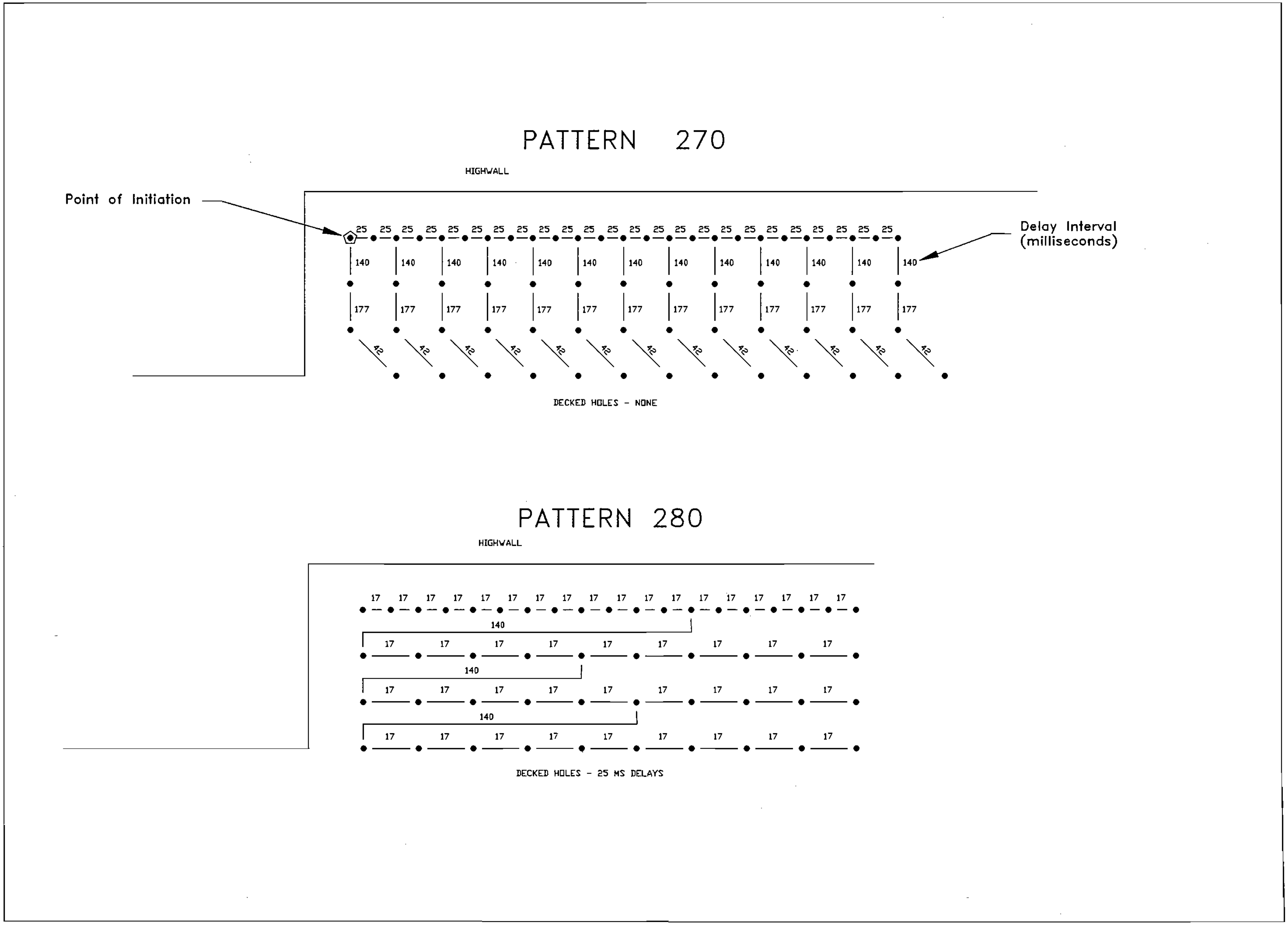
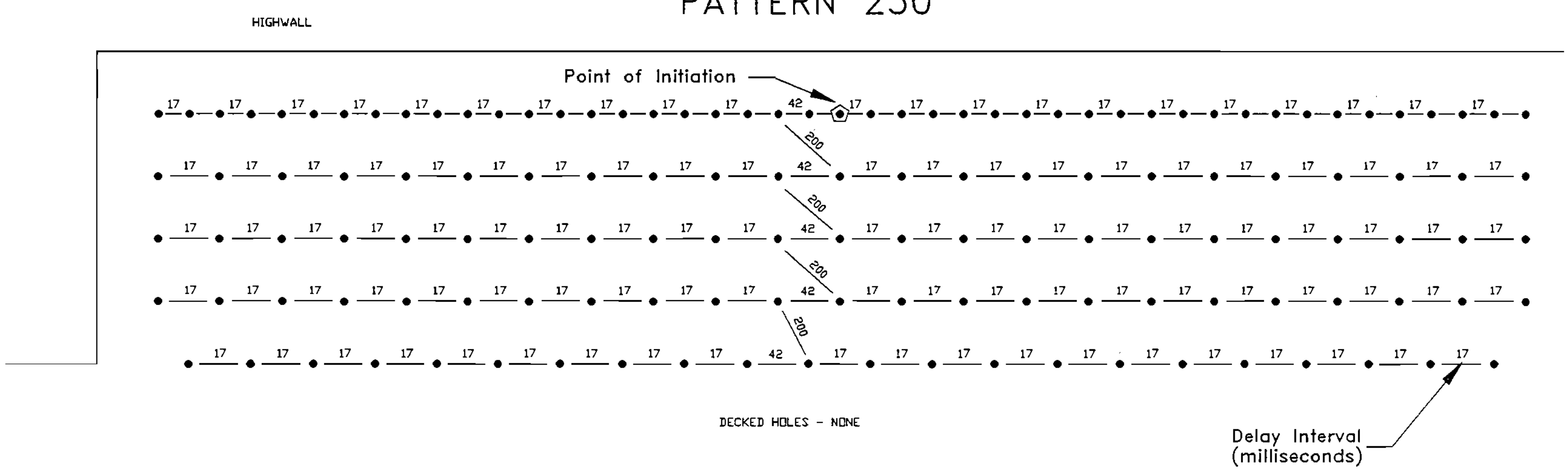


Figure 9 (cont.)
Cast Blast Patterns

PATTERN 250



PATTERN 260

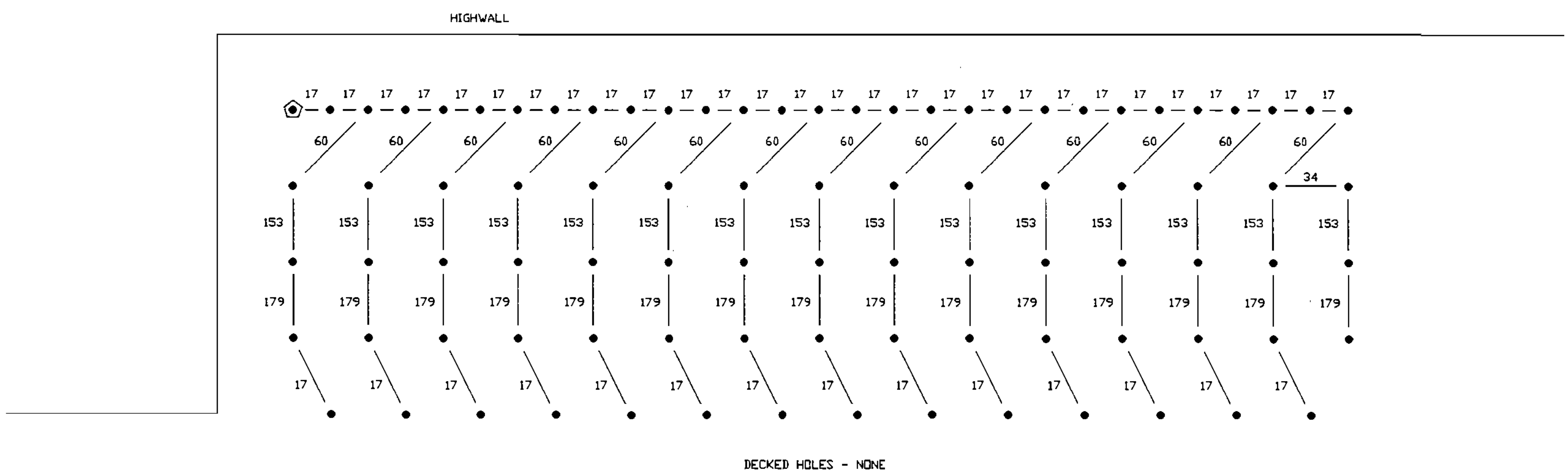
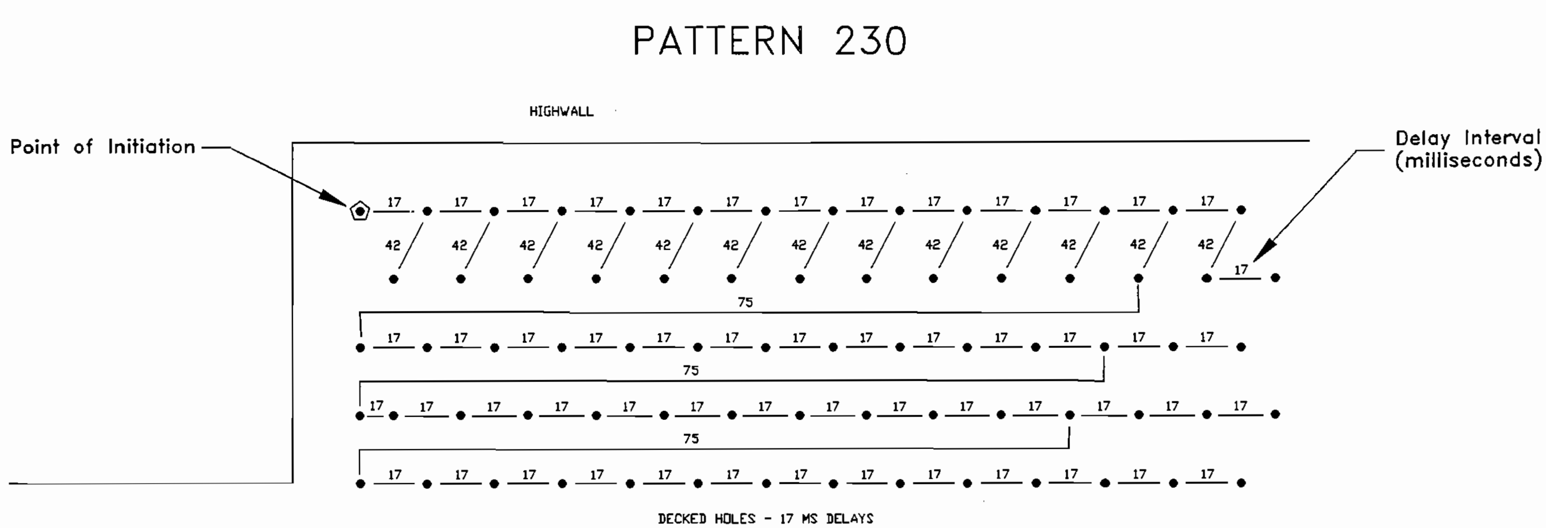


Figure 9 (cont.)
Cast Blast Patterns



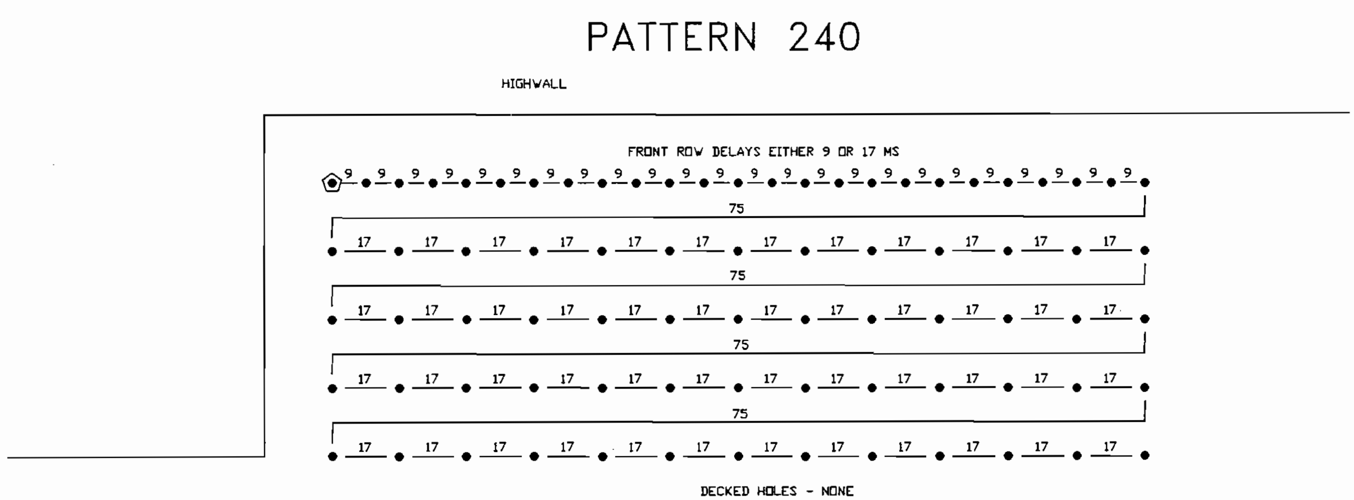


Figure 9

Cast Blast Patterns

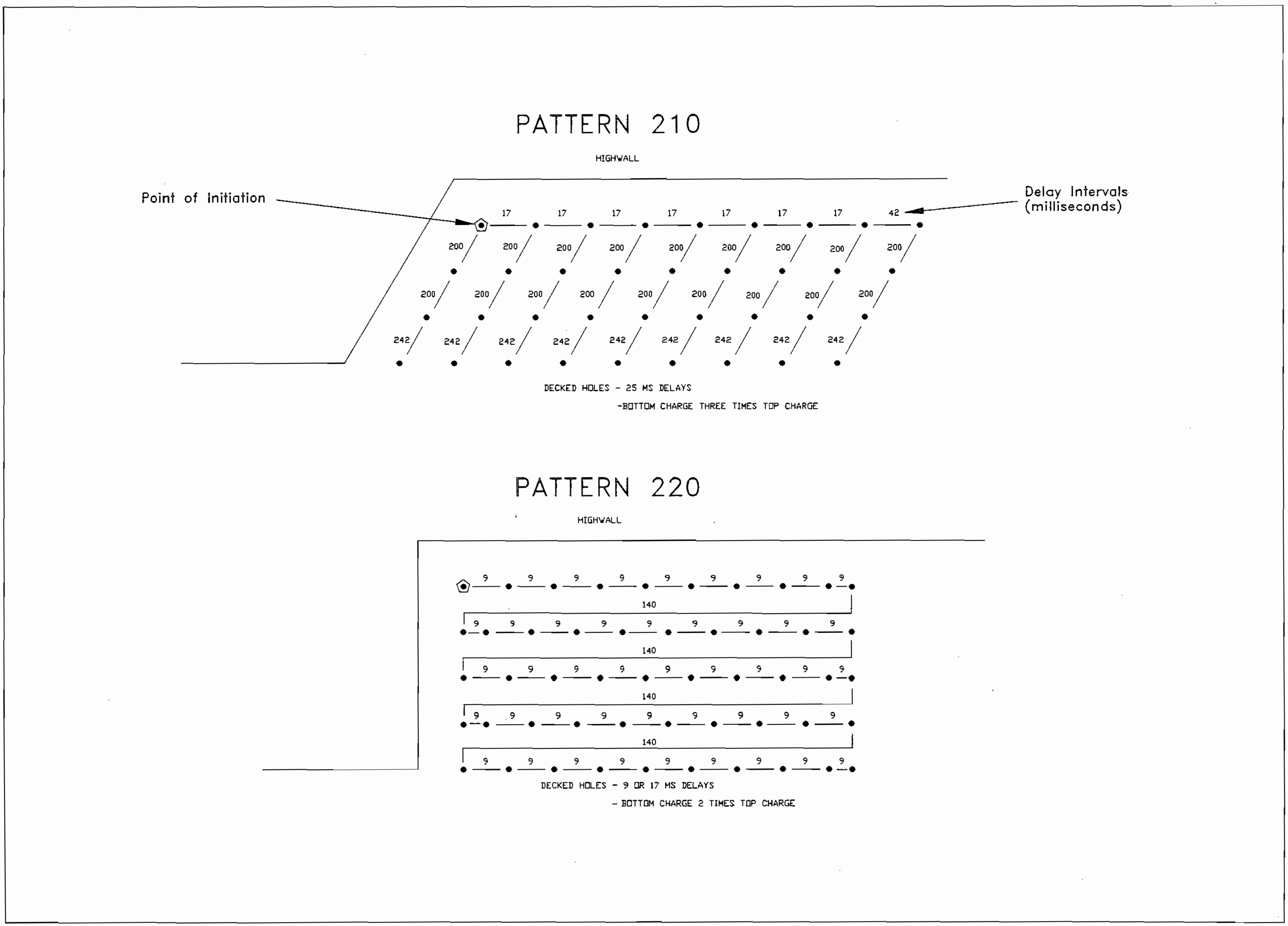
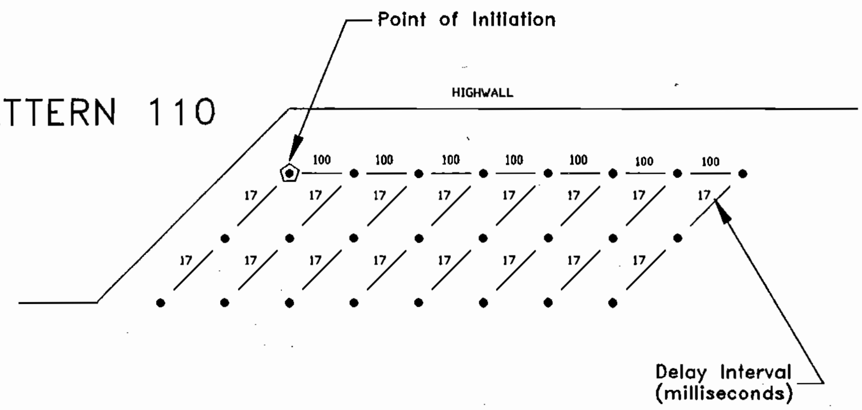
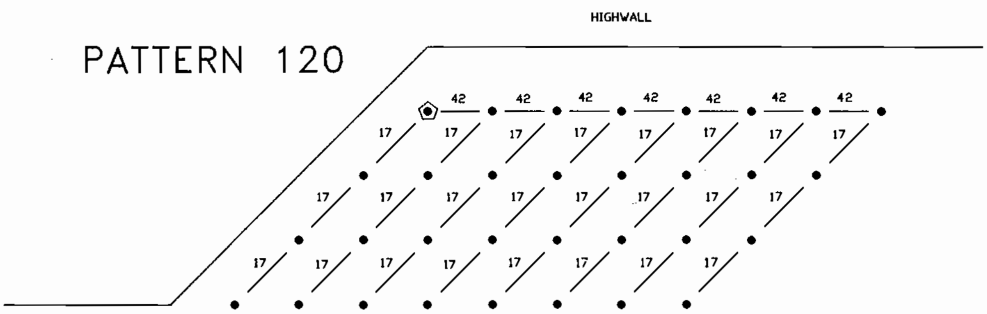


Figure 8 Conventional Blast Patterns

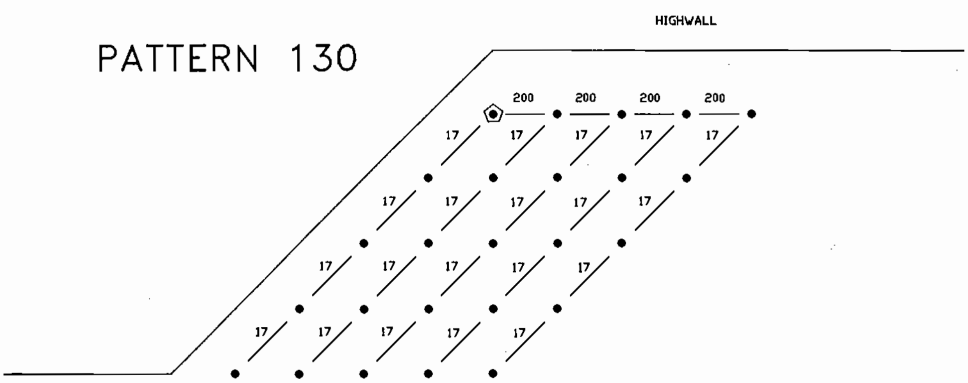
PATTERN 110



PATTERN 120



PATTERN 130



PATTERN 140

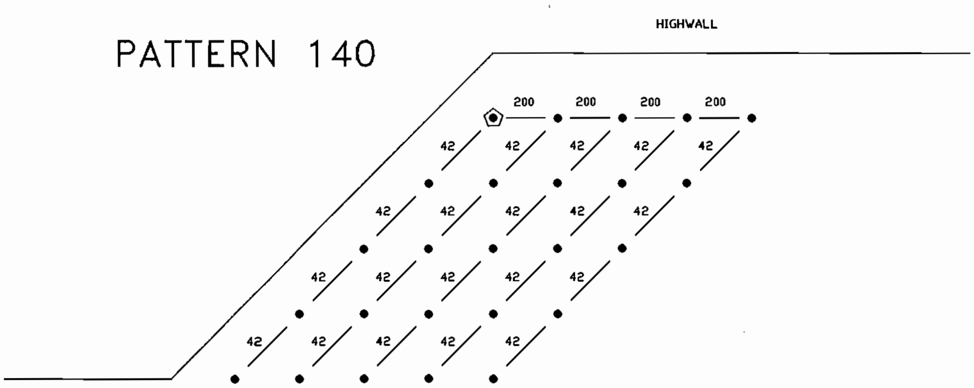


FIGURE 7

IDNR TWO-CUT STUDY, COMPLAINTS TO
EXPLOSIVE WEIGHT PER DELAY CORRELATION

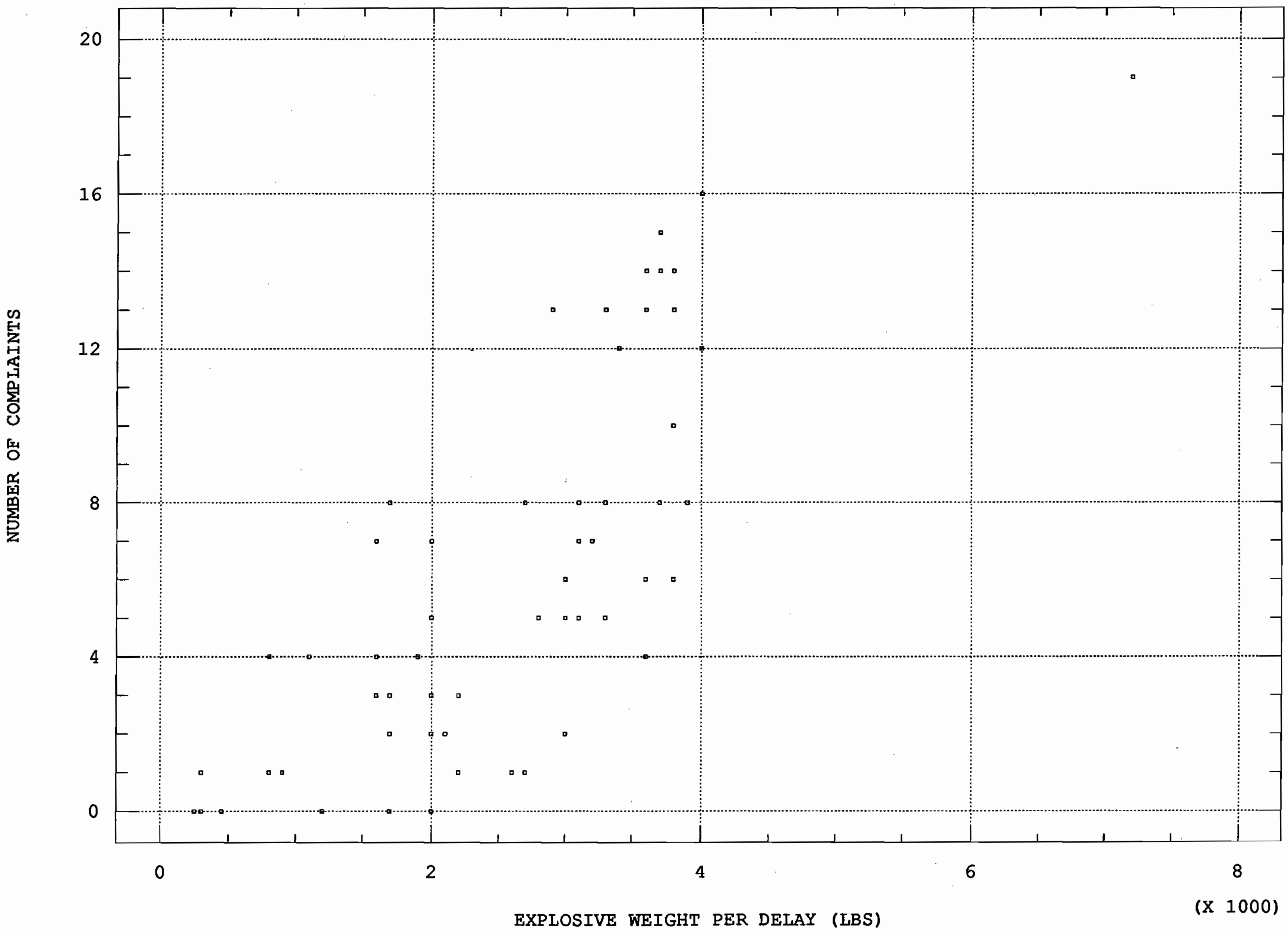


FIGURE 6

IDNR TWO-CUT STUDY, COMPLAINTS TO TOTAL
EXPLOSIVE WEIGHT CORRELATION

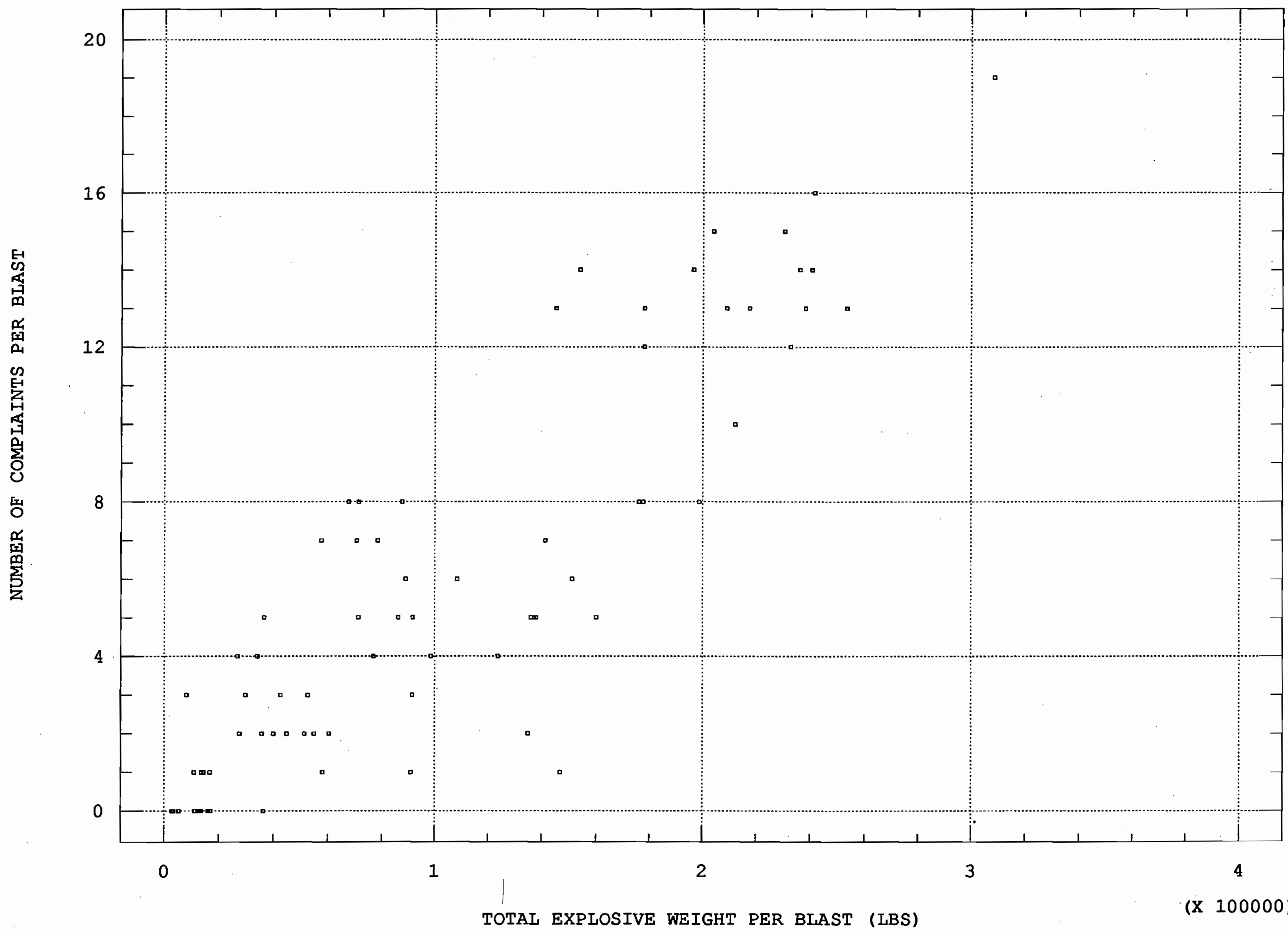


FIGURE 5

AYRSHIRE MINE WEIGHT OF EXPLOSIVES PER

DELAY PER BLAST 1986 THROUGH 1991

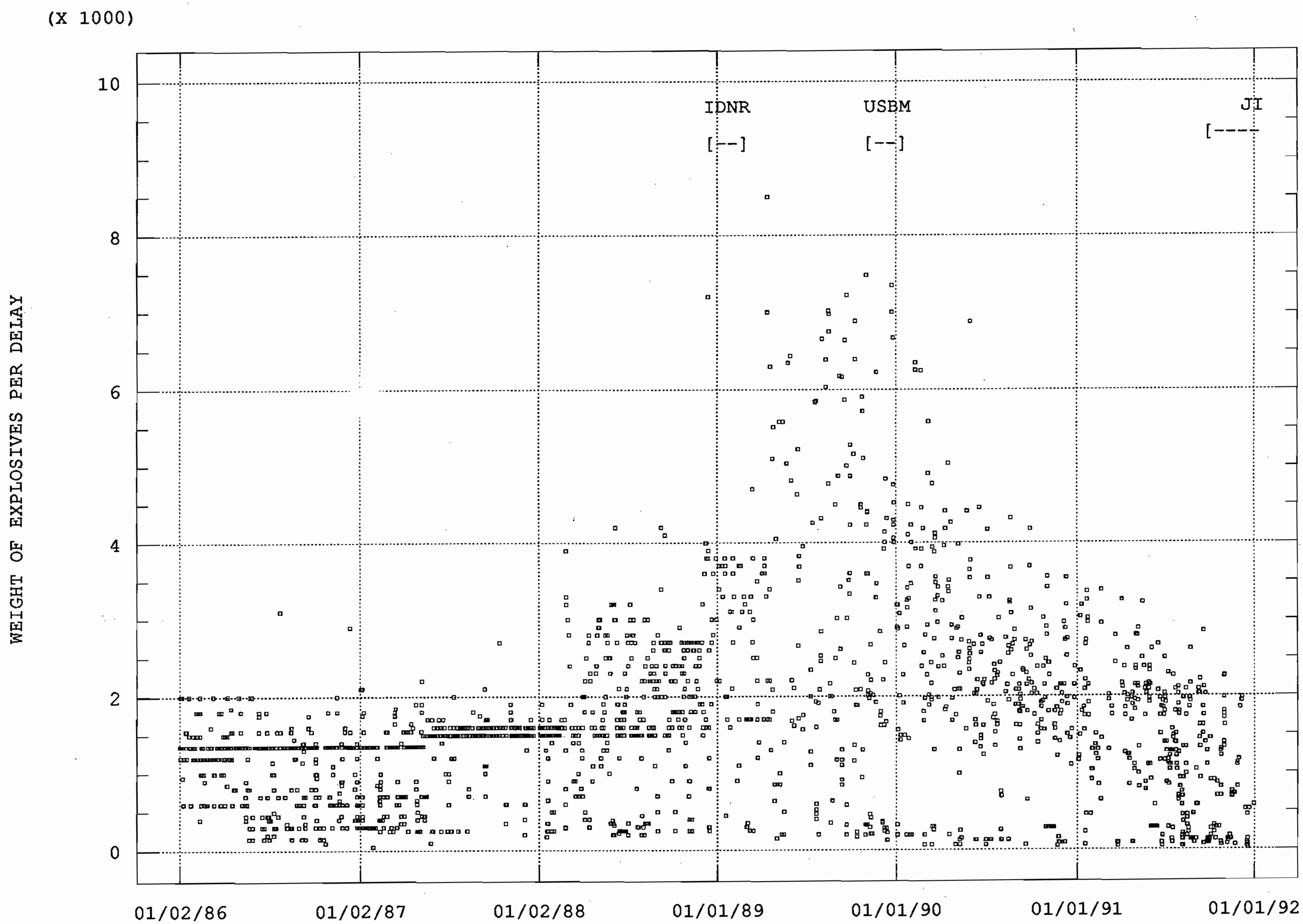
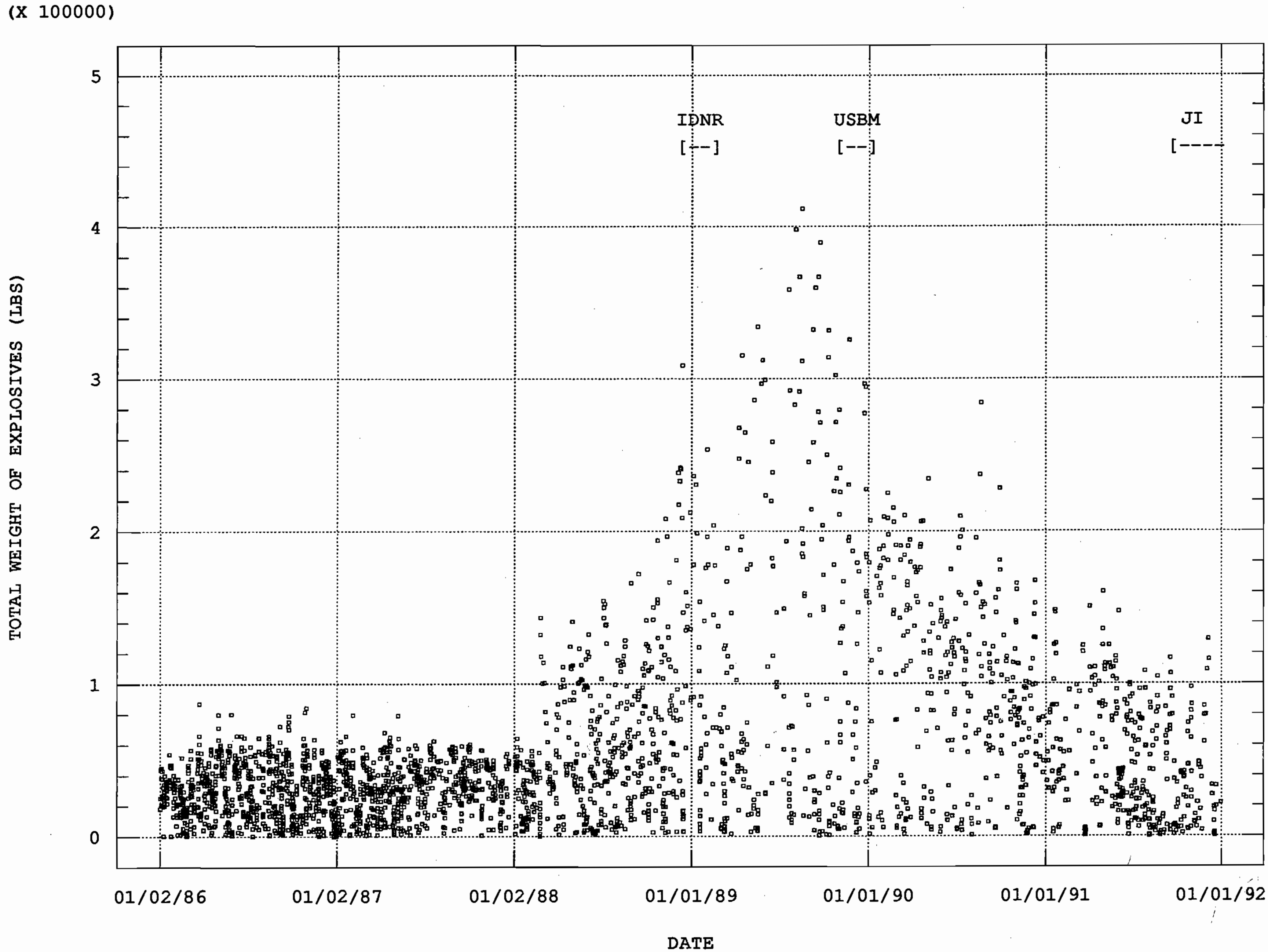
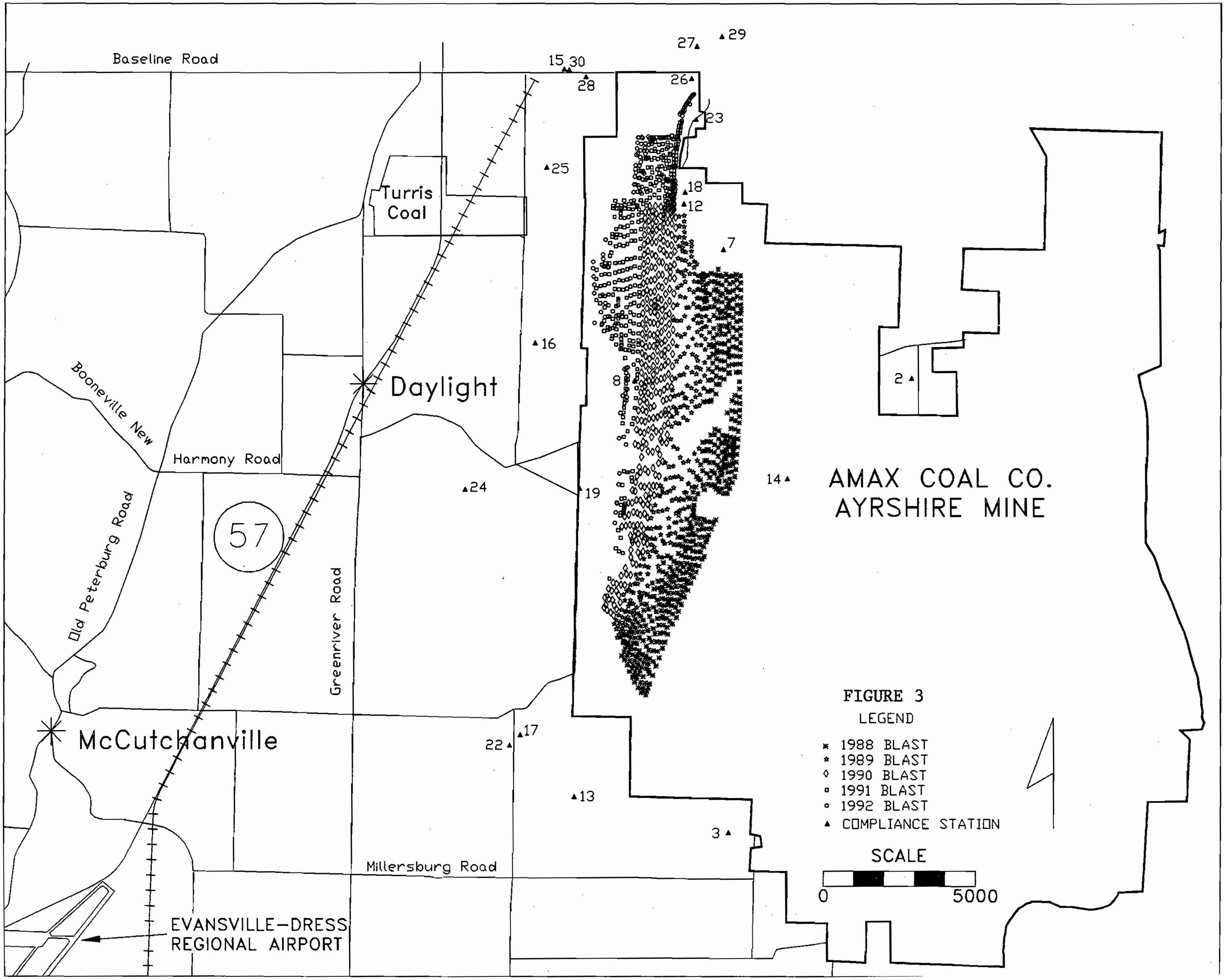


FIGURE 4

AYRSHIRE MINE TOTAL WEIGHT OF EXPLOSIVES
PER BLAST 1986 THROUGH 1991

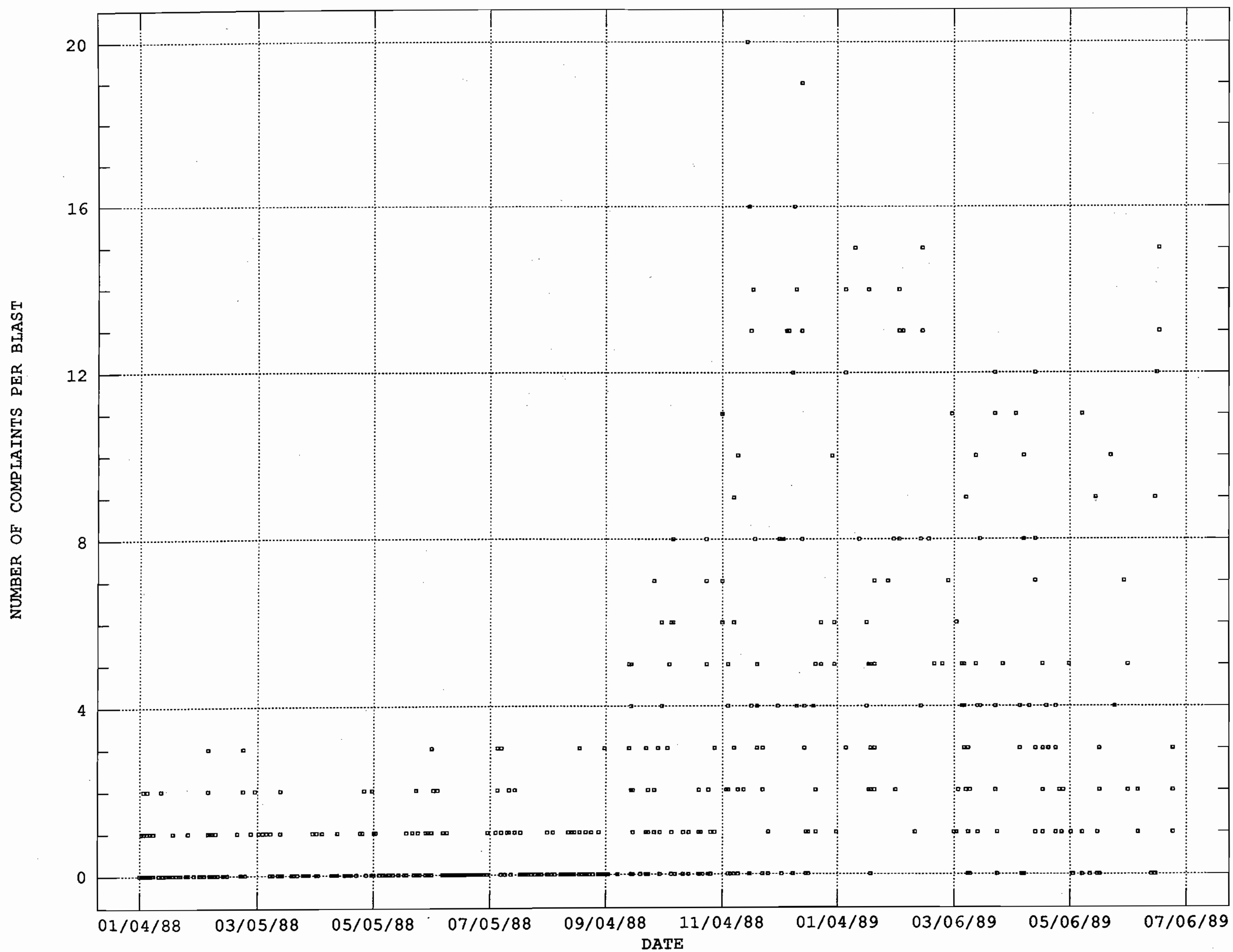




AMAX COAL CO.
AYRSHIRE MINE
Baseline Road
Turris Coal
Daylight
Booneville New
Harmony Road
Old Peterburg Road
57
Greenriver Road
McCutchanville
Millersburg Road
EVANSVILLE-DRESS REGIONAL AIRPORT
15 30 28 27 29 26 23 25 18 12 7 16 2 8 19 14 24 22 17 13 3
LEGEND
1988 BLAST
1989 BLAST
1990 BLAST
1991 BLAST
1992 BLAST
COMPLIANCE STATION
SCALE
0
5000

FIGURE 3

FIGURE 2. COMPLAINT DATA SUMMARY
IDNR STUDY AND OSM FIELD SURVEY



ground vibrations by systematically removing parts of the blast data from figure 19.

Figure 20 shows all vibration data at compliance stations from January 1988 to April 1992. By eliminating 1986 and 1987 blast data all but one particle velocity above 1.0 in/s is removed and a few points above the 95% confidence line are lost. These lost points correspond to vibrations recorded at station 14 as the mine operated around the church property. Therefore, vibrations at any of the compliance stations in front of the highwall exceeded 1.0 in/s only once.

Figure 21 shows all conventional and cast blast vibrations. Presplit, box-cut and parting blast data are removed from the graph because few complaints were generated. The removed points are shown on figure 22. As a result, most points remaining on figure 21 fall below the 95% confidence line. Figure 22 blasts generally resulted in higher vibration amplitudes and are mostly located above the mean line. This is possibly attributable to higher explosive confinement of the blast patterns.

Figure 23 plots vibration data at station 14 for the conventional and cast blasts of figure 21. In large part, amplitudes fall below the mean line and notably never exceed the 95% confidence line. Furthermore, for only the cast blasts of figure 23 as shown on figure 24 amplitudes at station 14 fall below the mean line all but three times. This necessitates a distinction between station 14 data and the remaining data to illustrate the vibration differences of spoil side and highwall monitoring locations. The data will be discussed in two groups: one represents the compliance station data in front of the highwall and the second compliance station (14) data behind the highwall. Interestingly, the loss of data points in figure 24 between the mean and 95% confidence line infer that conventional blasts caused higher vibrations at the church than cast blasts at comparable scaled distances.

Figure 25 plots amplitude data for conventional and cast blasts at all compliance stations in front of the highwall. The spread of the data extends to the 95% confidence line as opposed to the station 14 data that is mostly below the mean line. The conclusion to this point is that blasts result in higher amplitudes at monitoring locations in front of the mine than behind the mine. Any regression analysis for the purpose of predicting ground vibrations in front of the highwall would be inaccurate if station 14 data were included.

Cast blast data are shown in figure 26 except for station 14. All points with a scaled distance greater than 200 ft/lb$^{1/2}$ are removed. Figure 27 plots the conventional blasts removed from figure 25 with different markers for station 14. Noteworthy are the number of station 14 points between the mean and 95%

confidence lines. This was not observed for the cast blasts where most points fell below the mean. Contrary to the cast blast data, station 14 vibrations for conventional blasts are sometimes higher than predicted by the mean line. A possible cause is the higher degree of explosive confinement in conventional blasts similar to pre-split and box-cut blasts.

Cast blast patterns can be divided into two groups; one group with data bounded by the IDNR 95% confidence line and the other with data bounded by the IDNR mean line. Figures 28 through 36 show vibration amplitudes at the compliance station for each cast blast pattern with station 14 data tagged differently.

Vibration amplitudes generated by patterns 210, 220, 230 and 240 (figures 28, 29, 30 and 31) generally fall between the mean and 95% confidence line, except for station 14 amplitudes which are below the mean line. Vibration amplitudes generated by patterns 250, 260, 270 and 280 (figures 32, 33, 34 and 35) are near or below the mean line at all compliance stations. Note that station 14 data is scarce for patterns 260, 270 and 280. After 1989, the highwall was further to the west and the church was rarely a compliance station.

Pattern 210 was the first cast blast pattern used at the mine during the summer of 1988. Although this pattern did not result in many complaints (figure 2), most damage was alleged to have occurred during this time. Figure 28 shows that more than half of compliance station data was for station 14. Data not at station 14 mostly fell between the mean and 95% confidence lines. Notably four data points exist at or above the 95% confidence line. Given the data separation of vibrations recorded in front of and behind the highwall, the worst-case vibration for any blast during use of this pattern would be predicted by the equation for the 95% confidence line.

Pattern 220 was used during the fall of 1988. The vibration amplitude distribution of this pattern is similar to pattern 210. Figure 29 shows that more than half of compliance station data was for station 14. Data not at station 14 mostly fell between the mean and 95% confidence lines. Again, the worst-case vibration of any blast during use of this pattern would be predicted by the equation for the 95% confidence line.

Pattern 230 was used in the winter and spring of 1989 and was the primary pattern in use during the IDNR study. Figure 29 shows that half of compliance station data was for station 14. As in patterns 210 and 220, the worst-case vibration of any blast during use of this pattern would be predicted by the equation for the 95% confidence line.

Pattern 240 vibration data shown on figure 31 had few points however the worst-case vibration would be predicted by the equation of the 95% confidence line.

Pattern 250 was used during the summer and fall of 1989. Two of these blasts were monitored during the USBM study. Figure 32 shows most of the vibration amplitudes below the mean line and the station 14 data well below the line. Only a few points are located above the mean line. The worst-case vibration of any blast during use of this pattern would be the equation for the mean line.

Pattern 260 and pattern 270 were used during most of 1990 and 1991. The vibration amplitudes are shown on Figures 33 and 34. These two patterns were monitored during the USBM study. The figures show only a few vibrations in excess of the mean line. Notably the station 14 points remain near the bottom of the data set as in earlier patterns. Again, the worst-case vibration of blast during use of this pattern would be the equation for the mean line.

Pattern 280 was used mostly during the winter and early spring of 1992. As shown on figure 35 the data points are widely scattered and occasionally located above the IDNR mean line. The energy flow of the pattern is similar to pattern 250 and so is the data distribution. Again, the worst-case vibration of any blast during use of this pattern would be the equation for the mean line.

Vibration amplitudes generated by pattern 200 (figure 36) hover around the mean line but two points are located near the 95% confidence line. Conclusions on vibrations are difficult because of the wide variety of patterns used in this classification. The worst-case vibrations of blasts used during this pattern would be a line in between the mean and 95% confidence lines.

BLAST DESIGN EFFECTS ON GROUND VIBRATIONS

Cast blast patterns 210, 220, 230 and 240 caused larger ground vibrations than patterns 250, 260, 270 and 280 at compliance stations. Subsequently, higher vibrations are predicted in Daylight and McCutchanville as a result of blasts using patterns 210, 220, 230 and 240. Worst-case vibrations in the study area are predicted with the equations obtained through statistical analysis of the IDNR study data. Peak vibrations were calculated for each cast blast between February 1988 and April 1992 in both Daylight and McCutchanville using the appropriate equation.

Central locations were chosen in Daylight and McCutchanville as points for ground vibration predictions; the intersection of Route 57 and Greenriver Road in Daylight (N205100,E372600) and the intersection of Old Petersburg Road and Whetstone Road in

McCutchanville (N216500,E382800). The scaled distance (distance/weight$^{1/2}$) of each blast in Daylight and McCutchanville was calculated using the state planar coordinates of the blast and explosive weight per delay as listed on the blast logs as follows.

$$SD = ((N_L - N_T)^2 + (E_L - E_T)^2)^{1/2}/W^{1/2}$$

where N_L and E_L are the northing and easting of the blast on the blast log, N_T and E_T are the northing and easting of the town and W is the maximum weight of explosive per delay.
Then the predicted peak particle velocities of each blast in Daylight and McCutchanville were calculated using the appropriate equation.

$$PPV = 55\ (SD)^{-1.19}\ \text{(mean)}$$
$$PPV = 137\ (SD)^{-1.19}\ \text{(95\% confidence)}$$

Pattern 200 vibrations were obtained by taking the average of the two values calculated by each equation. Table 4 lists the maximum particle velocities for each cast blast pattern that could occur in both towns.

Table 4. Worst-Case Ground Vibrations

Pattern	Daylight PPV (in/s)	McCutchanville PPV (in/s)
200	0.33	0.14
210	0.26	0.11
220	0.28	0.13
230	0.38	0.15
240	0.38	0.17
250	0.17	0.07
260	0.17	0.06
270	0.17	0.06
280	0.08	0.03

The potential worst-case vibration amplitude for any of the cast blast designs in Daylight and McCutchanville is 0.38 and 0.17 inches per second, respectively. These predicted values are approximately twice the highest levels recorded during the IDNR study (Daylight, 0.21 in/s and McCutchanville, 0.07 in/s) and about three times the highest levels of any recorded amplitudes during the USBM study (Daylight, 0.10 in/s, and McCutchanville, 0.06 in/s). The higher predicted levels are attributable to the conservative nature of the estimate based on the statistical analysis. It is highly unlikely that the actual vibration amplitudes of any pattern listed in Table 4 ever equaled on exceeded the predicted values in either Daylight or McCutchanville.

FINDINGS

- Complaints lodged with OSM and IDNR in 1988 and the first half of 1989 are largely in response to blasts at the Ayrshire mine. Complaints not attributable to Ayrshire blasts did not correlate with one another to indicate problems with another mine.

- Complaints lodged with OSM and IDNR in 1988 and the first half of 1989 are largely in response to cast blasts. Conventional, box-cut, pre-split and parting blasts generated fewer complaints.

- The number of complaints correlate highly to the total weight of explosives used in a blast during the IDNR study period. Elements such as weather conditions, or time-dependent ground conditions do not correlate well with complaints.

- The total pounds of explosives and pounds of explosives detonated per delay for each blast peaked in the summer of 1989. One blast over 400,000 pounds was detonated and the maximum explosives detonated in one delay was 8,500 pounds.

- Box-cut and pre-split blasts were more likely to generate higher vibration amplitudes than conventional and cast blasts at compliance structures. Since few complaints were attributable to box-cut and pre-split blasts, potential worst-case vibrations in Daylight and McCutchanville were not predicted.

- Conventional blasts generated higher vibration amplitudes at station 14 than cast blasts of comparable scaled distances.

- Cast blasts generated lower ground vibrations at station 14 than at compliance stations in front of the mine. A spoil bound compliance station is an inappropriate monitoring location when other structures are located in advance of the mine.

- Ground vibration data for each cast blast design were obtained during studies by IDNR, USBM or JI with the exception of patterns 210 and 240.

- Cast blast patterns 210, 220, 230 and 240 generated higher vibrations than 250, 260, 270 and 280. The IDNR study primarily monitored pattern 230 and the USBM study monitored 260 and 270. The vibration amplitudes from cast blasts prior to July 1989 generally caused greater vibration amplitudes than later blasts.

- The calculated worst-case vibration amplitude in Daylight for cast blasts is 0.38 in/s.

- The calculated worst-case vibration amplitude in McCutchanville for cast blasts is 0.17 in/s.

- The worst-case vibration amplitudes developed in this report are approximately two times higher than any recorded amplitudes in Daylight and McCutchanville.

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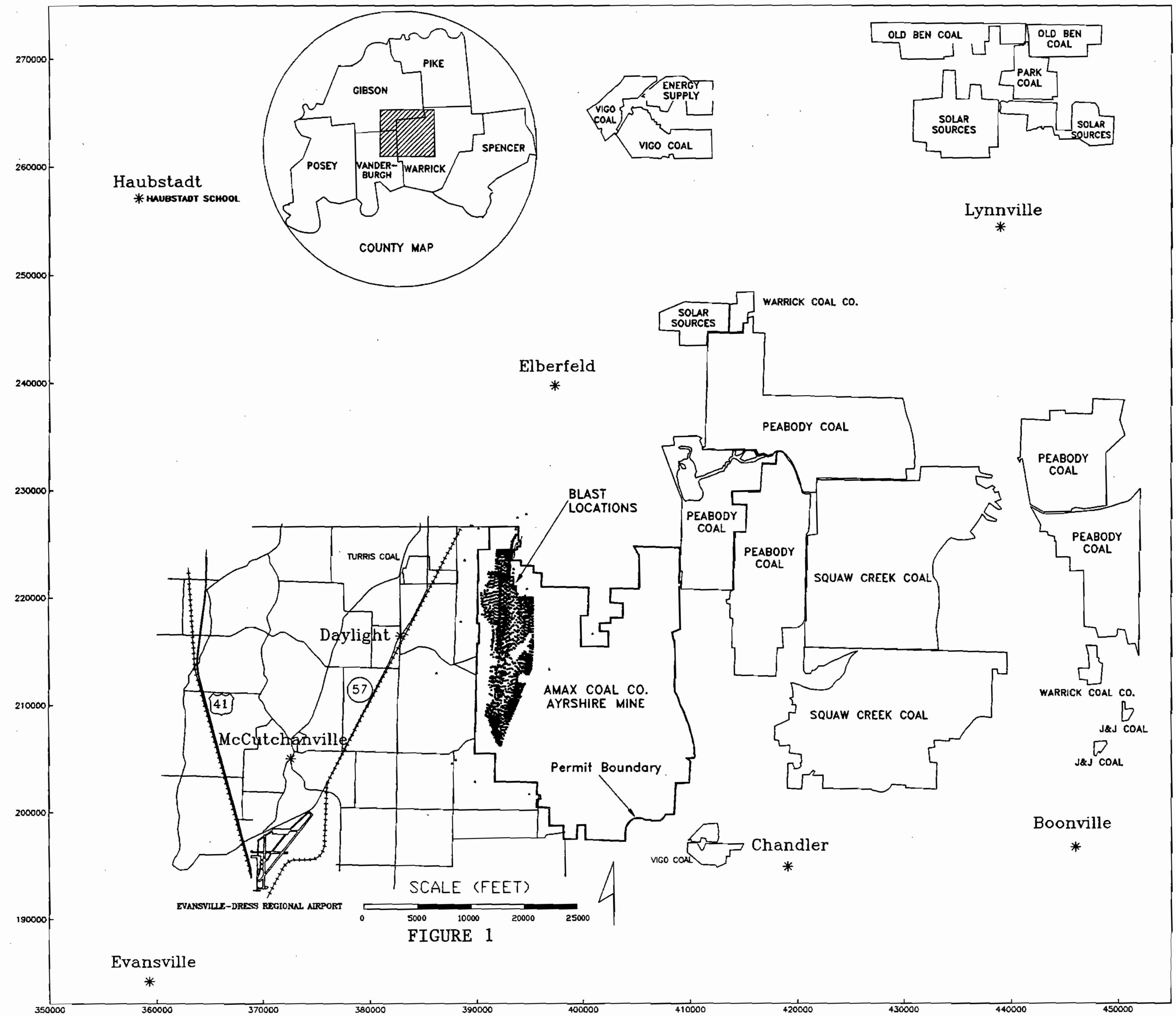
OLD BEN COAL
OLD BEN COAL
PARK COAL
SOLAR SOURCES
SOLAR SOURCES
VIGO COAL
ENERGY SUPPLY
VIGO COAL
PIKE
GIBSON
POSEY
VANDER-BURGH
WARRICK
SPENCER
COUNTY MAP
Haubstadt
HAUBSTADT SCHOOL
Lynnville
SOLAR SOURCES
WARRICK COAL CO.
Elberfeld
PEABODY COAL
PEABODY COAL
PEABODY COAL
PEABODY COAL
PEABODY COAL
PEABODY COAL
SQUAW CREEK COAL
SQUAW CREEK COAL
BLAST LOCATIONS
TURRIS COAL
Daylight
57
41
McCutchanville
AMAX COAL CO.
AYRSHIRE MINE
Permit Boundary
WARRICK COAL CO.
J&J COAL
J&J COAL
Boonville
Chandler
VIGO COAL
SCALE (FEET)
0
5000
10000
20000
25000
EVANSVILLE-DRESS REGIONAL AIRPORT
Evansville
270000
260000
250000
240000
230000
220000
210000
200000
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390000
400000
410000
420000
430000
440000
450000
FIGURE 1

FIGURE 24

COMPLIANCE STATION DATA

JANUARY 1988 THROUGH APRIL 1992

CAST BLASTS AT STATION 14

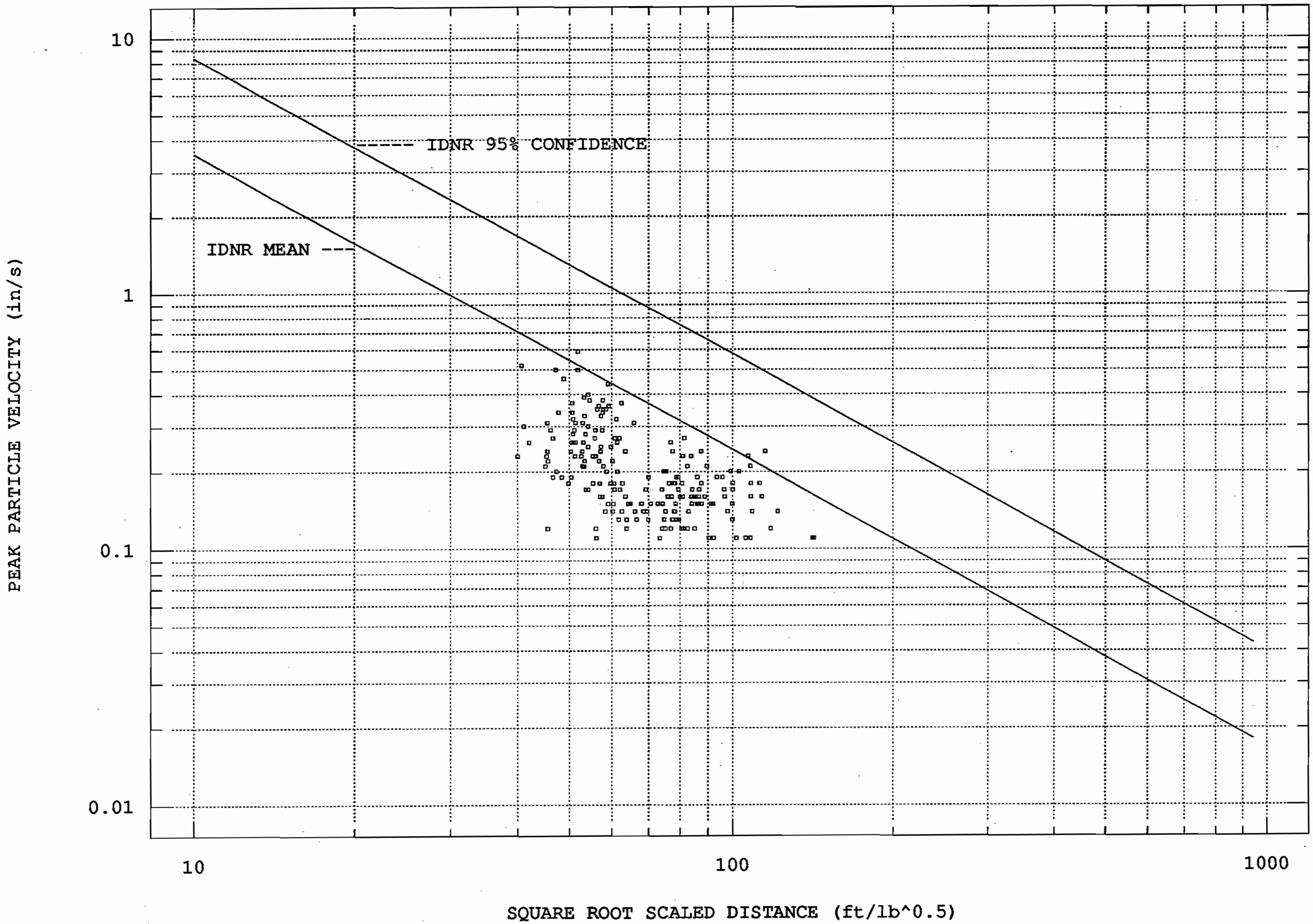

FIGURE 23

COMPLIANCE STATION DATA

JANUARY 1988 THROUGH APRIL 1992

CONVENTIONAL AND CAST BLASTS AT STATION 14

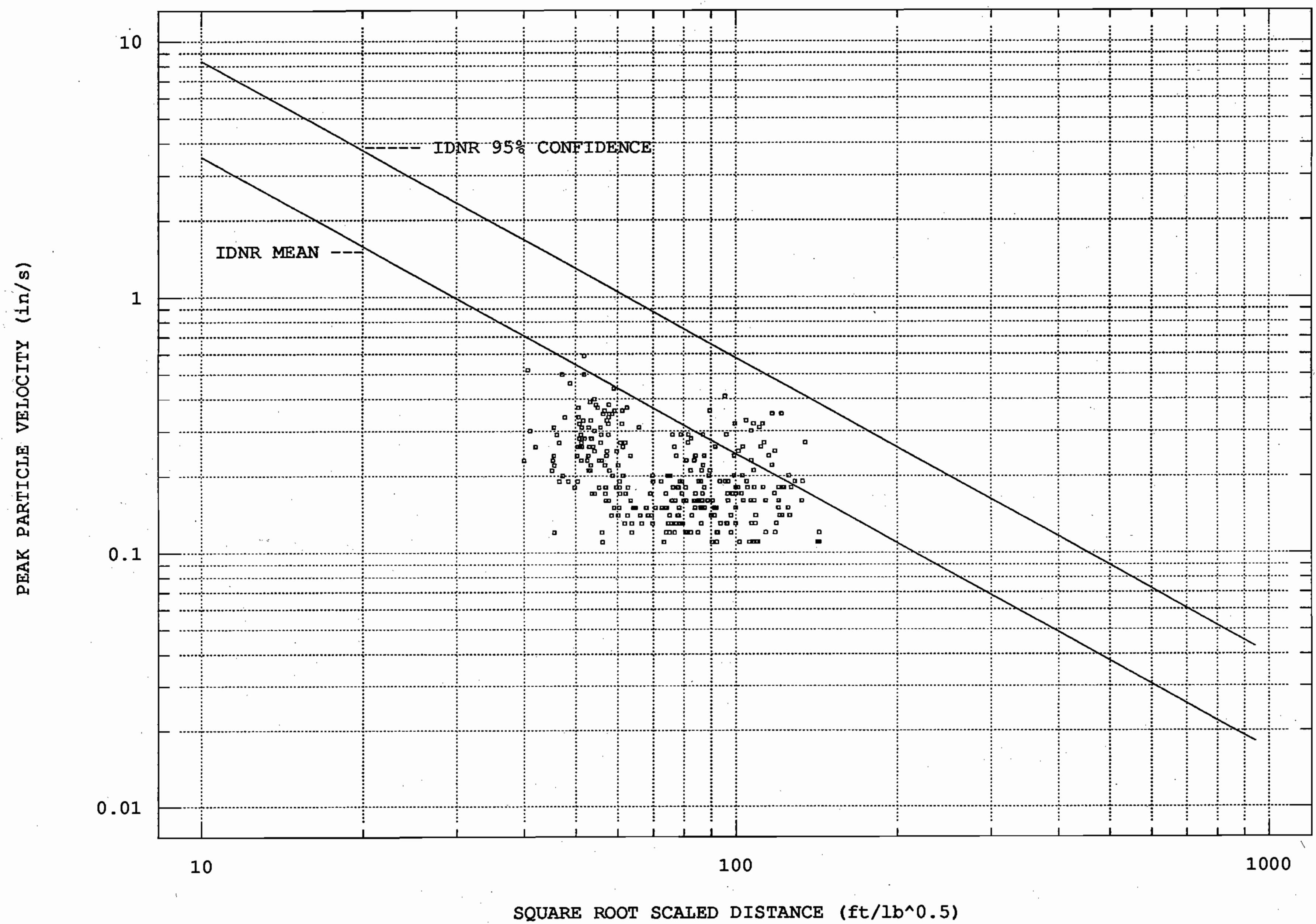

FIGURE 22

COMPLIANCE STATION DATA

JANUARY 1988 THROUGH APRIL 1992

BOX-CUT, PRE-SPLIT AND PARTING BLASTS

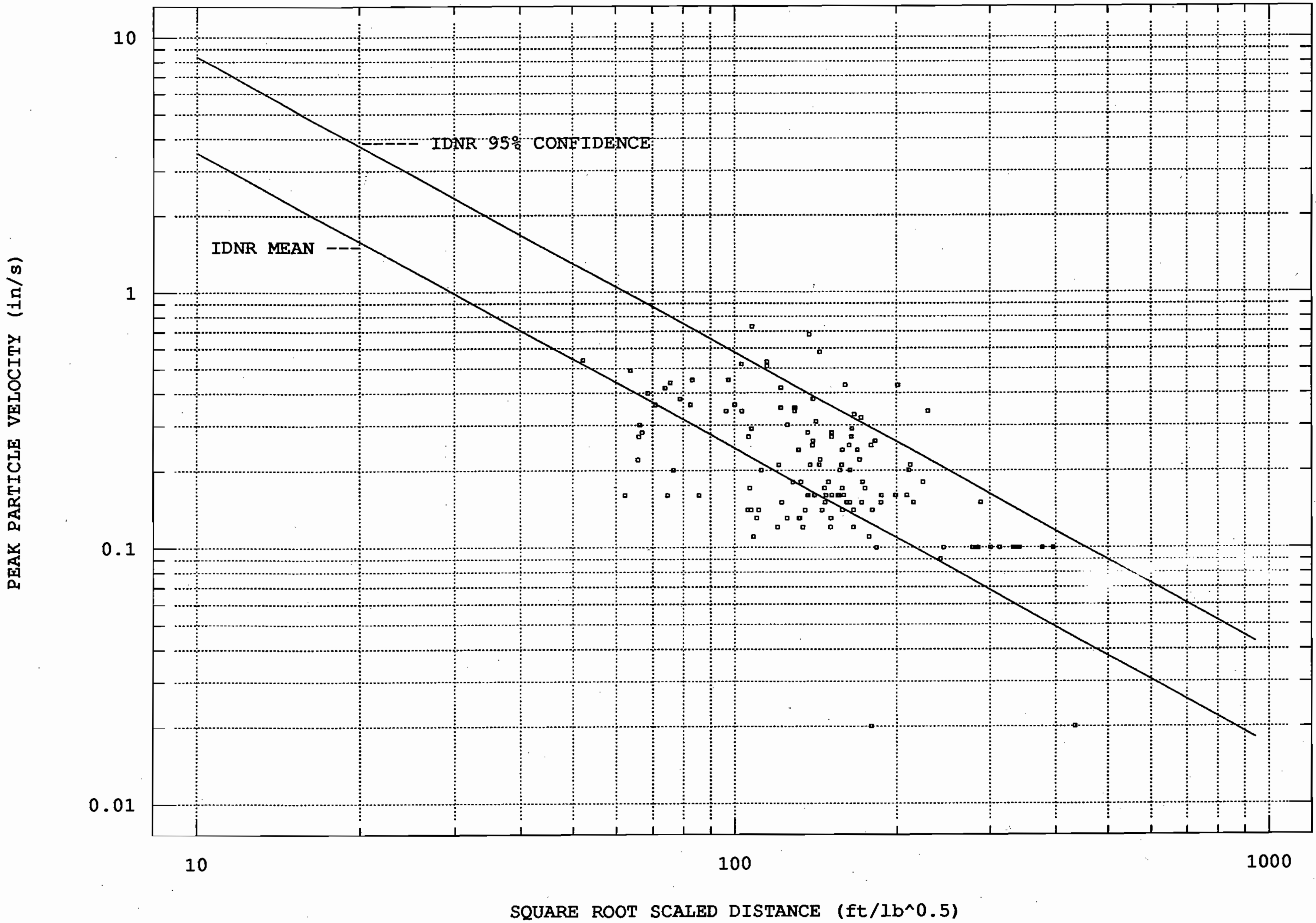

FIGURE 21

COMPLIANCE STATION DATA

JANUARY 1988 THROUGH APRIL 1992

CONVENTIONAL AND CAST BLASTS

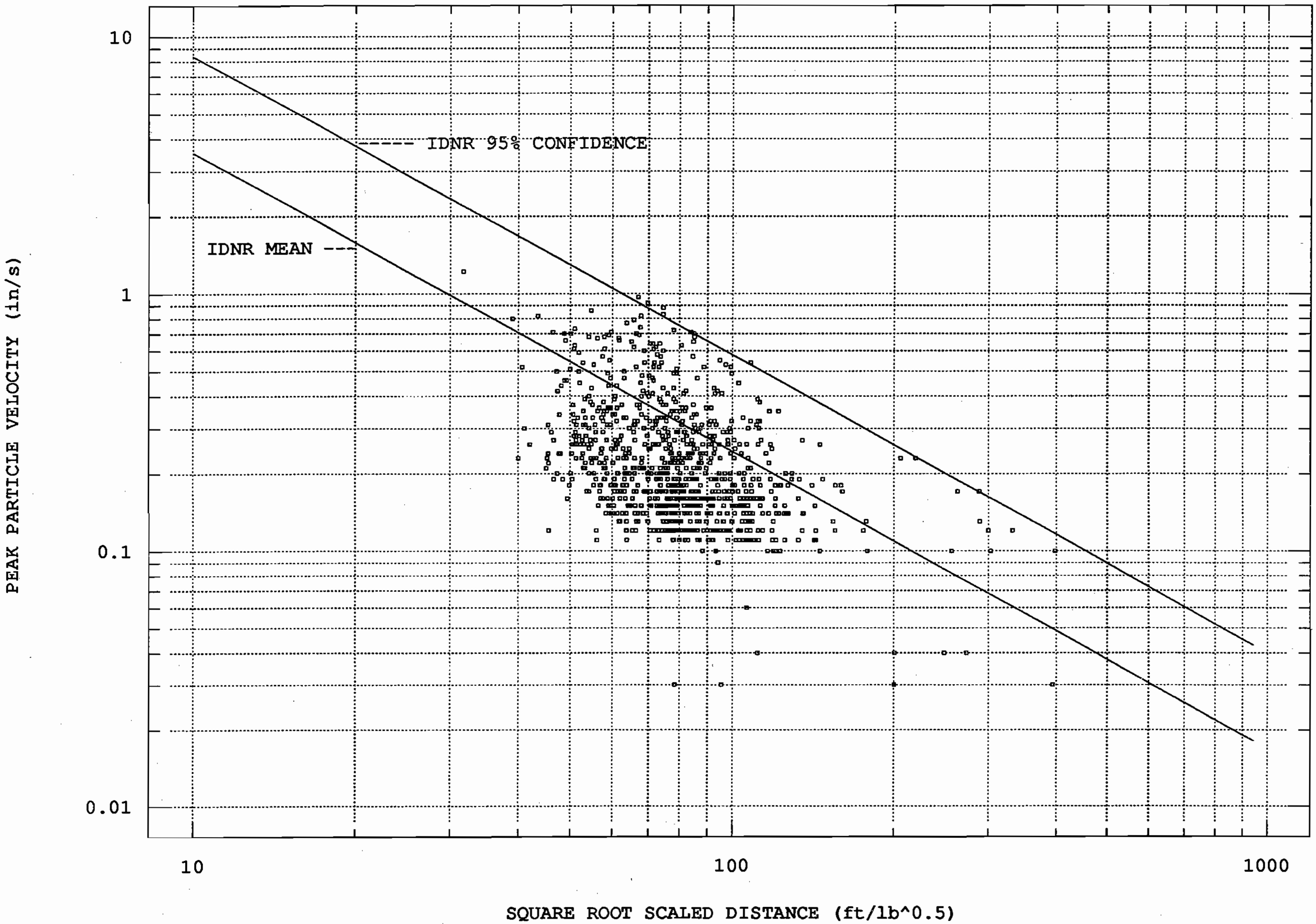

FIGURE 20

COMPLIANCE STATION DATA

JANUARY 1988 THROUGH APRIL 1992

ALL BLASTS

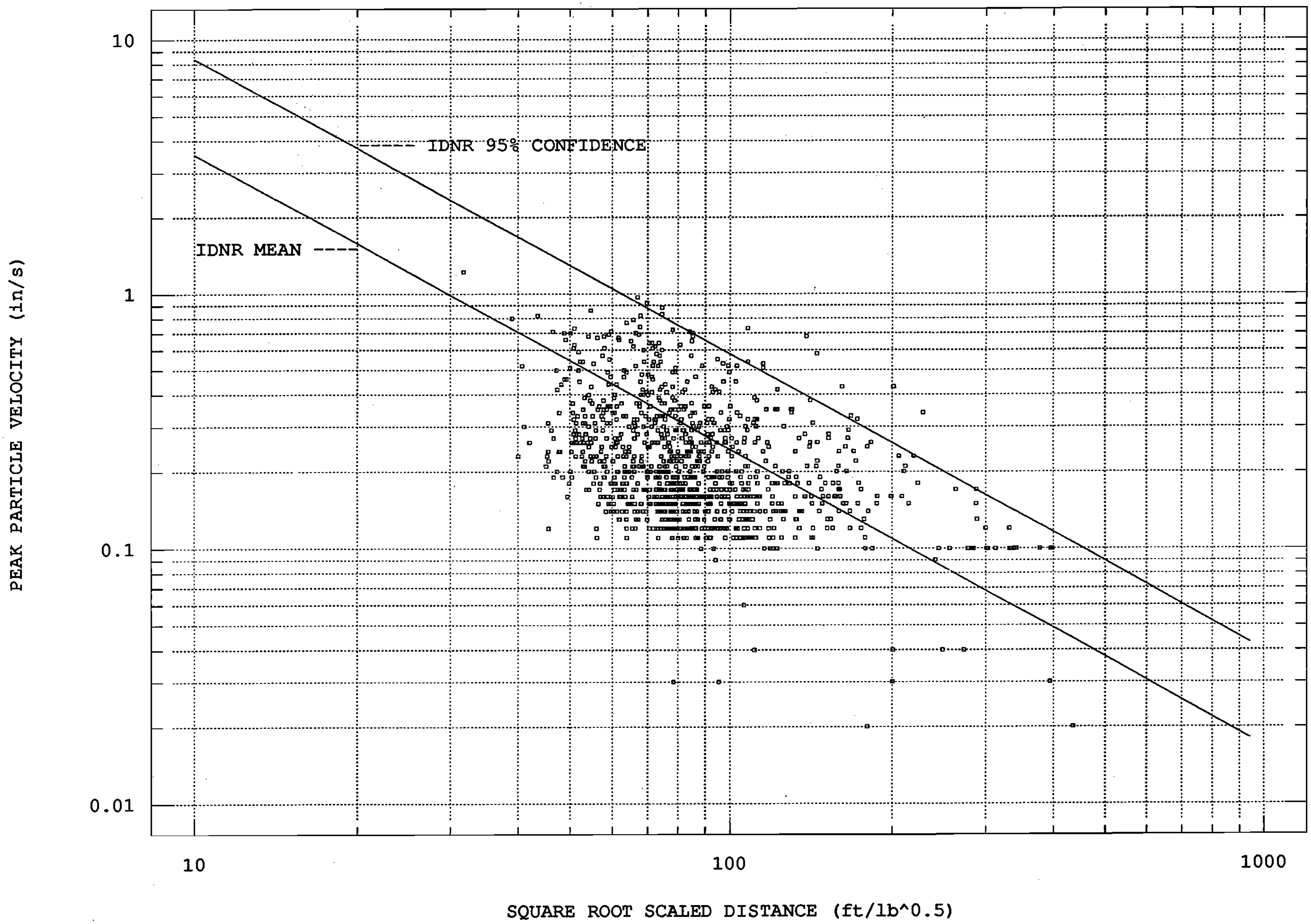

FIGURE 19

COMPLIANCE STATION DATA

JANUARY 1986 THROUGH APRIL 1992

ALL BLASTS

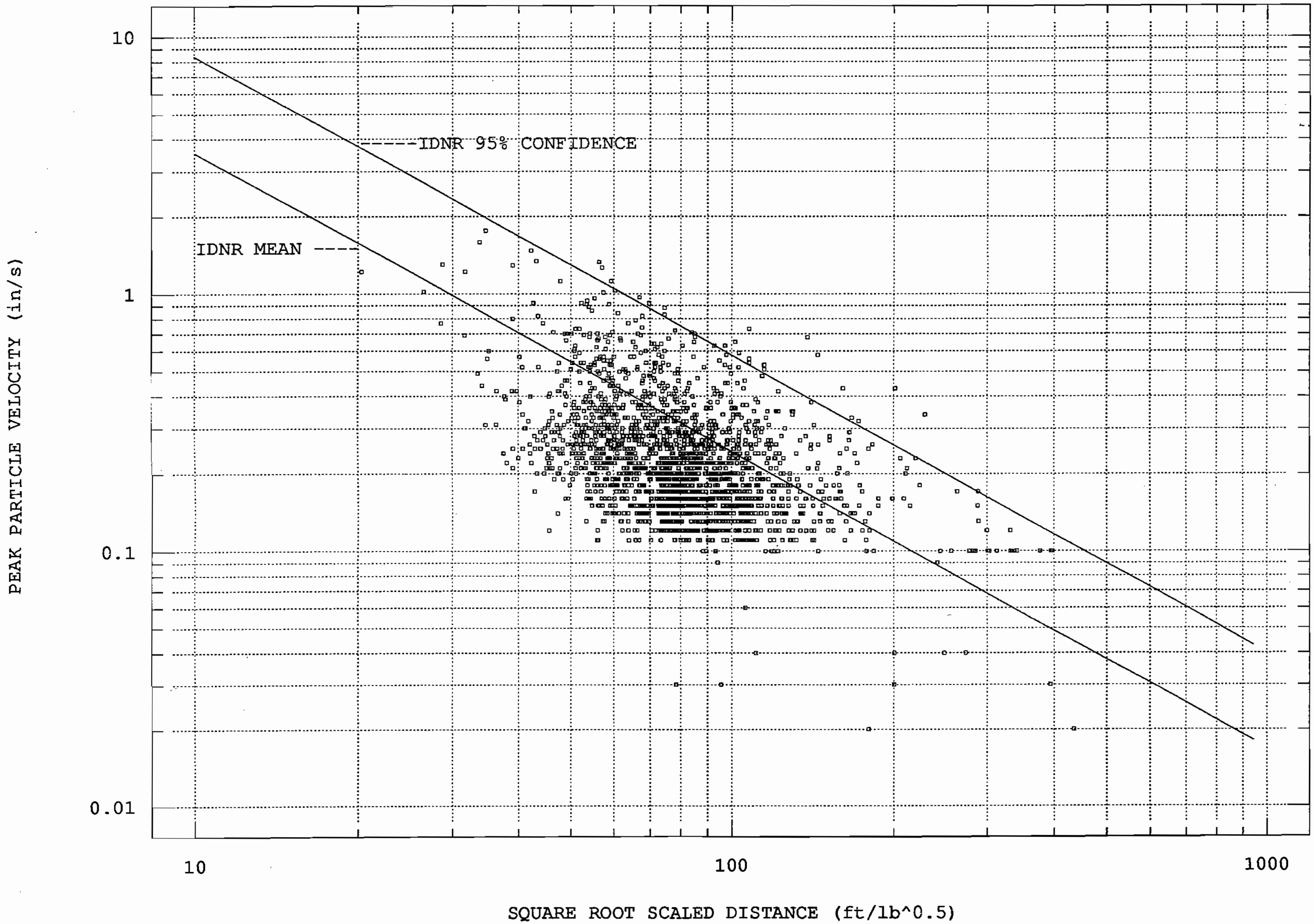

FIGURE 18

1989 IDNR STUDY REGRESSION LINES (CAST BLASTS)

WITH IDNR AND USBM PEAK PARTICLE VELOCITY DATA

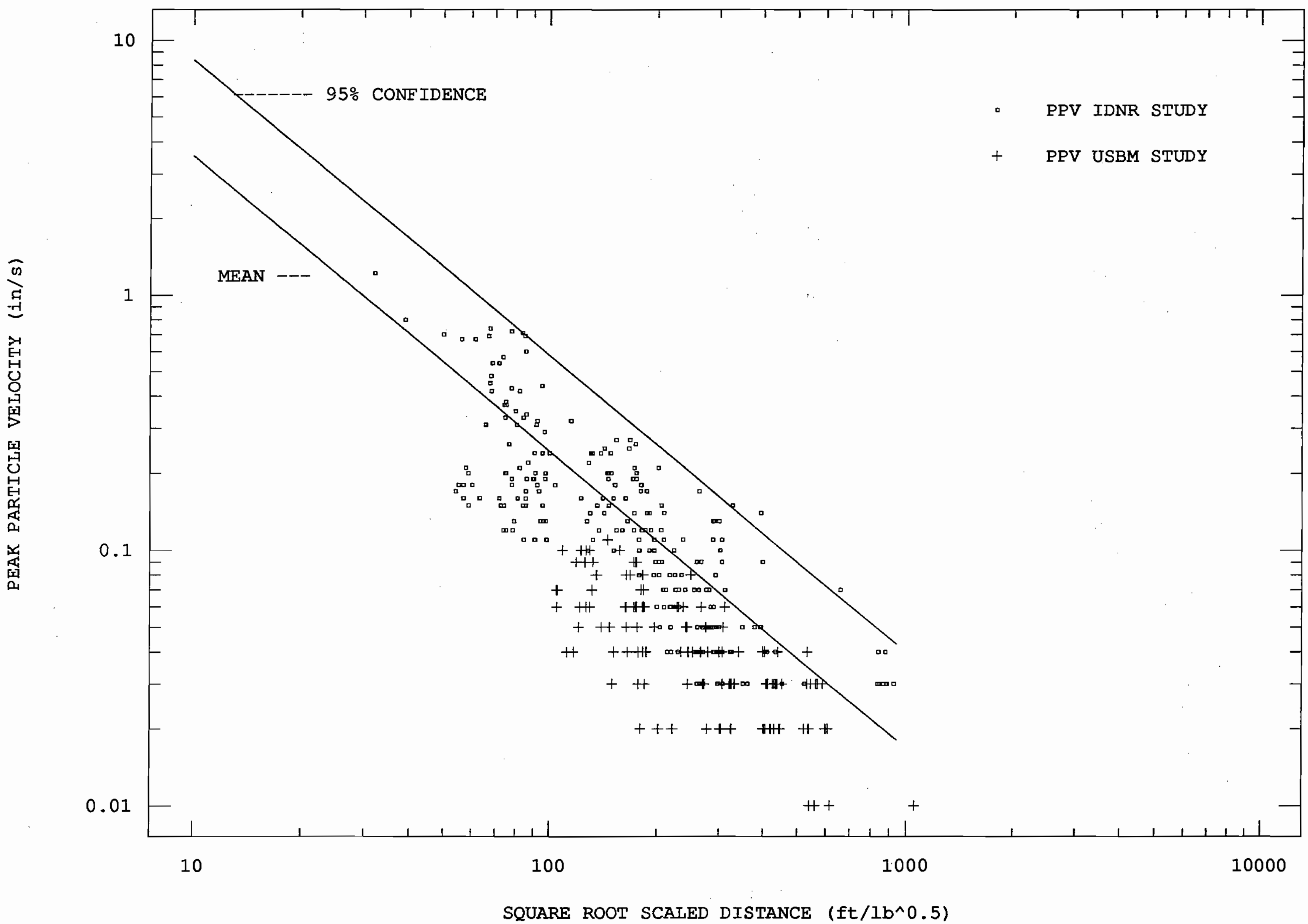

FIGURE 17

ENERGY FLOW DIAGRAM

CAST BLAST PATTERNS

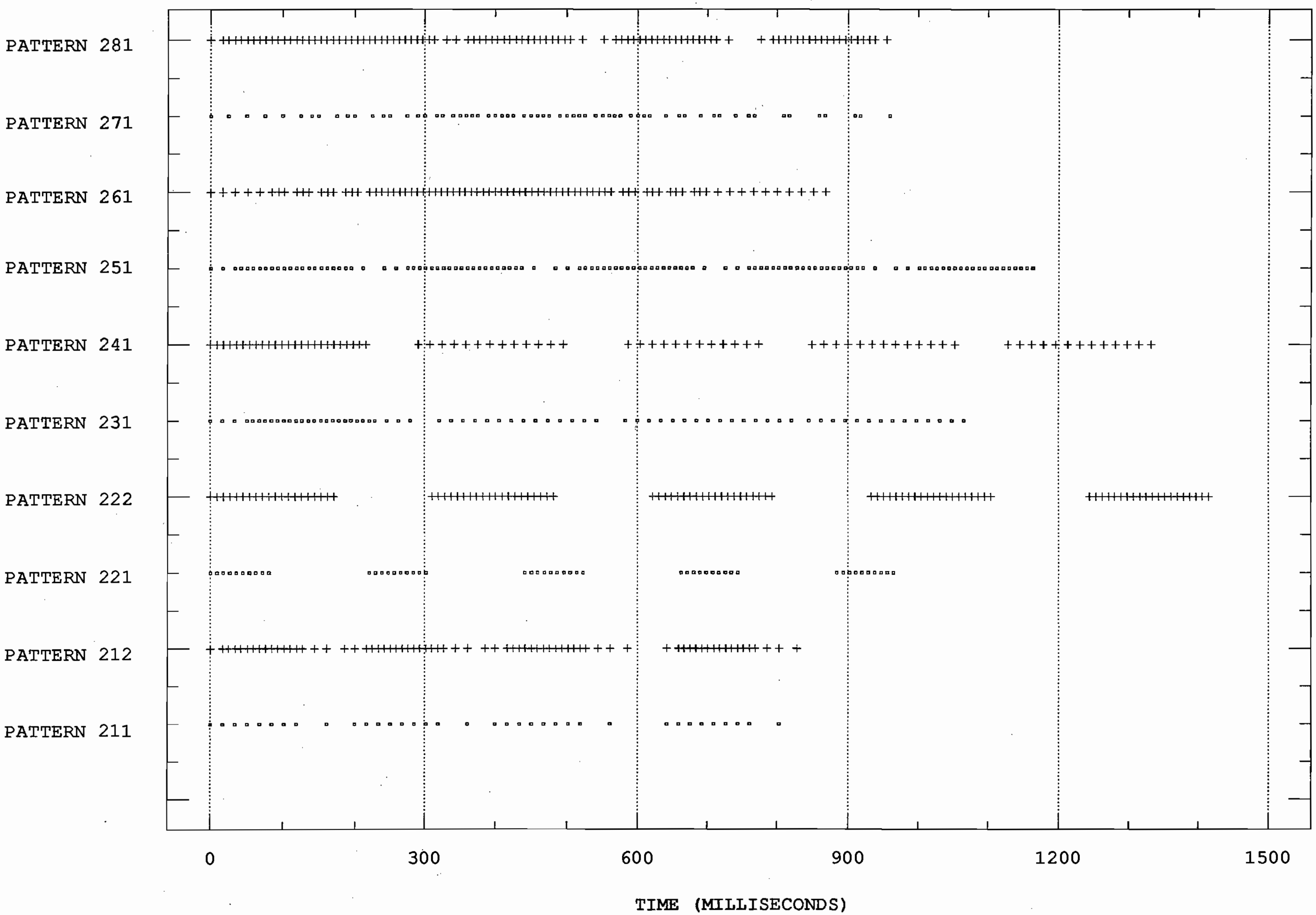

FIGURE 29

COMPLIANCE STATION DATA

CAST BLAST PATTERN 220

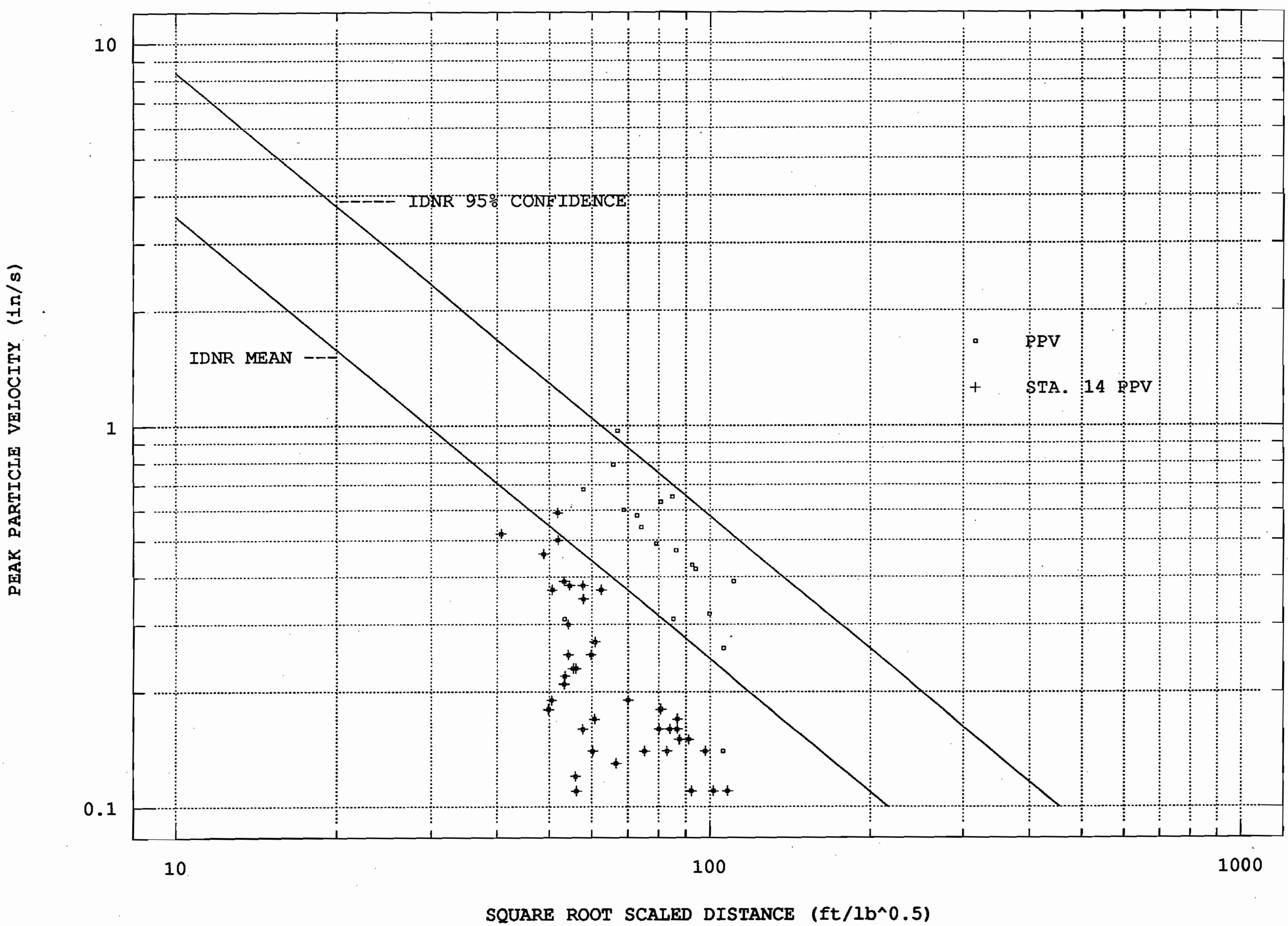

FIGURE 30

COMPLIANCE STATION DATA

CAST BLAST PATTERN 230

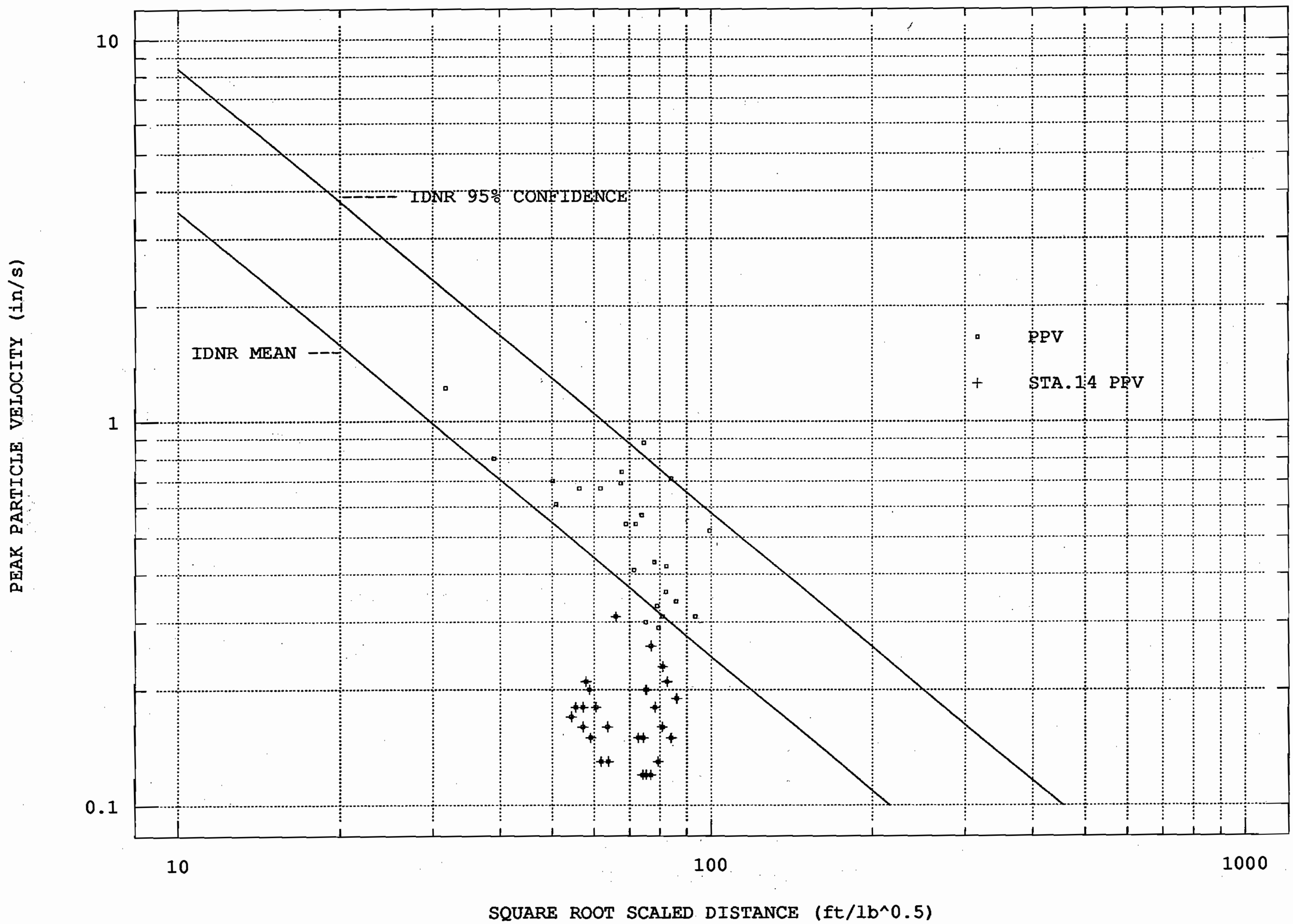

FIGURE 11

1989 IDNR STUDY

BLAST LOCATIONS BY BLAST PATTERN SERIES

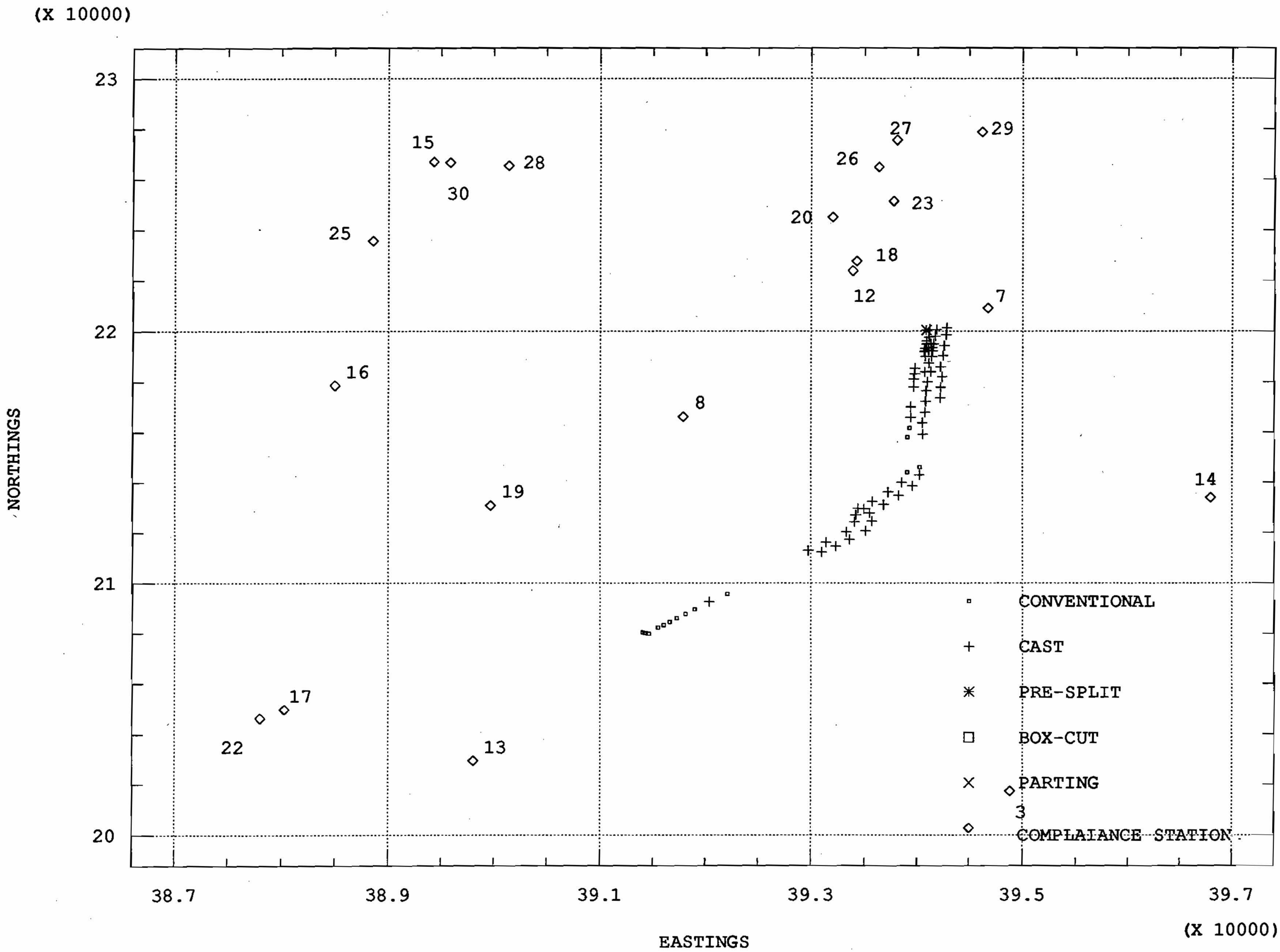

FIGURE 12

1990 USBM STUDY

BLAST LOCATIONS BY BLAST PATTERN SERIES

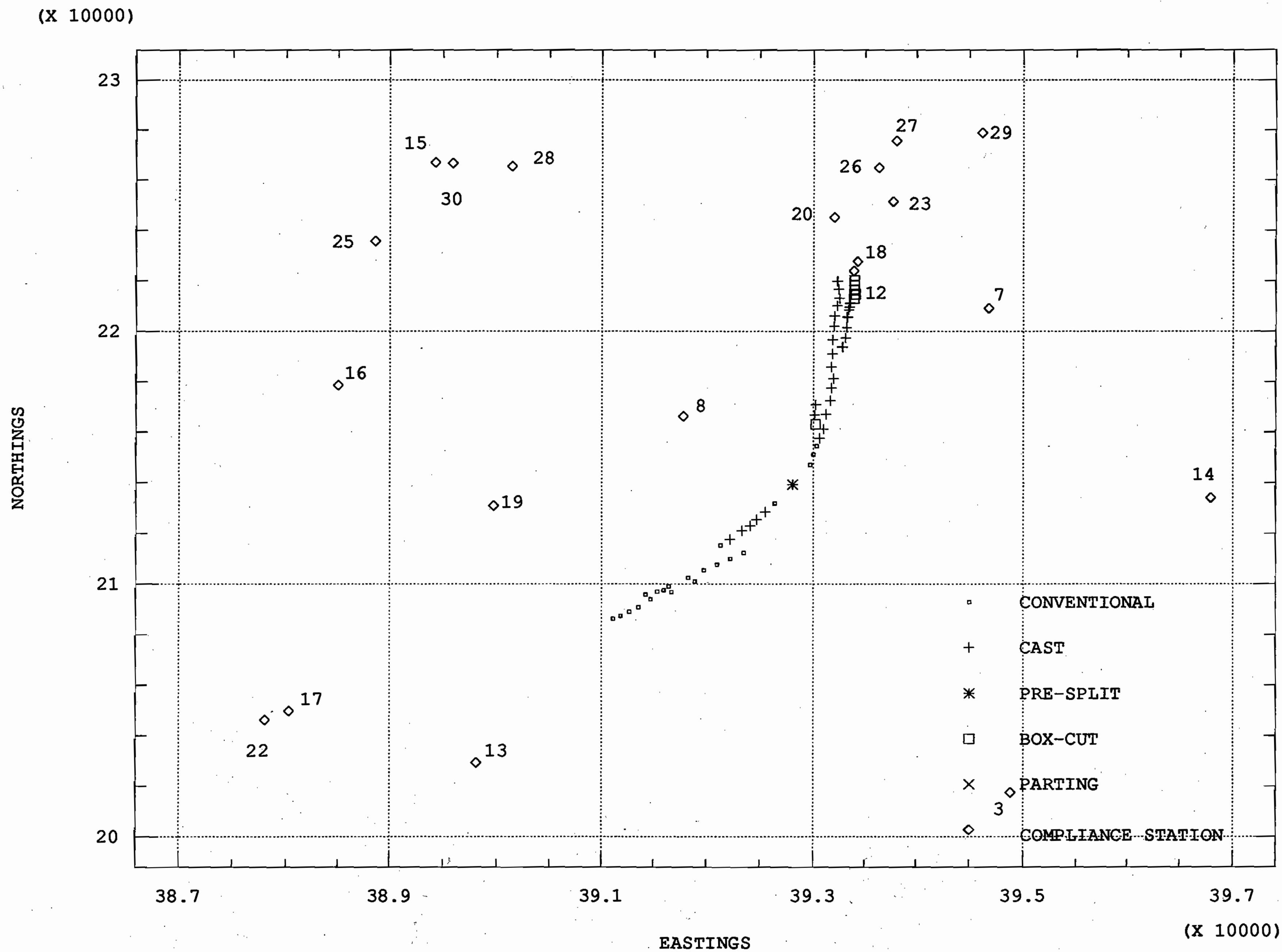

FIGURE 13

1992 JOINT INVESTIGATION

BLAST LOCATIONS BY BLAST PATTERN SERIES

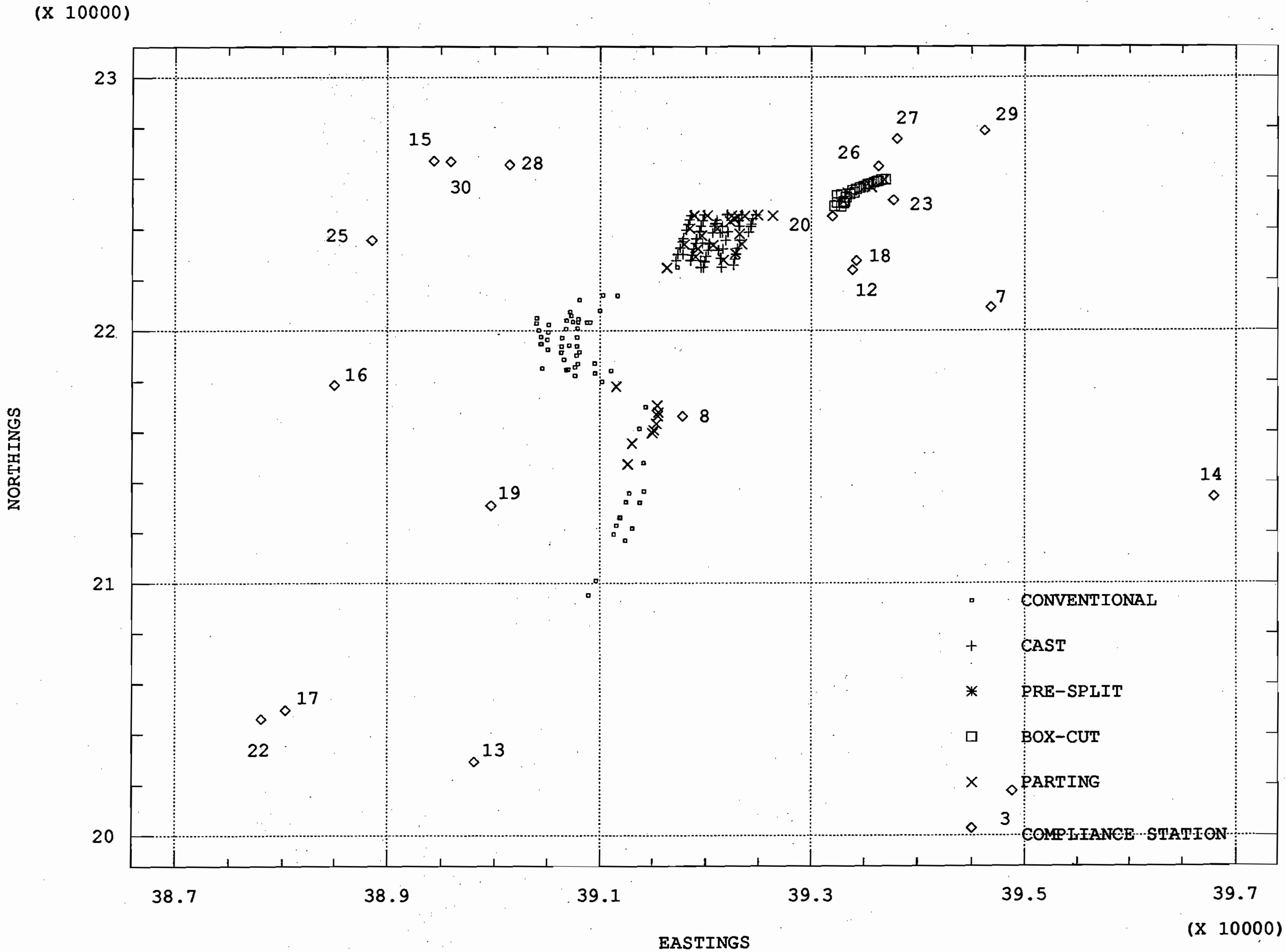

FIGURE 14

AVERAGE COMPLAINTS PER

CONVENTIONAL BLAST PATTERN

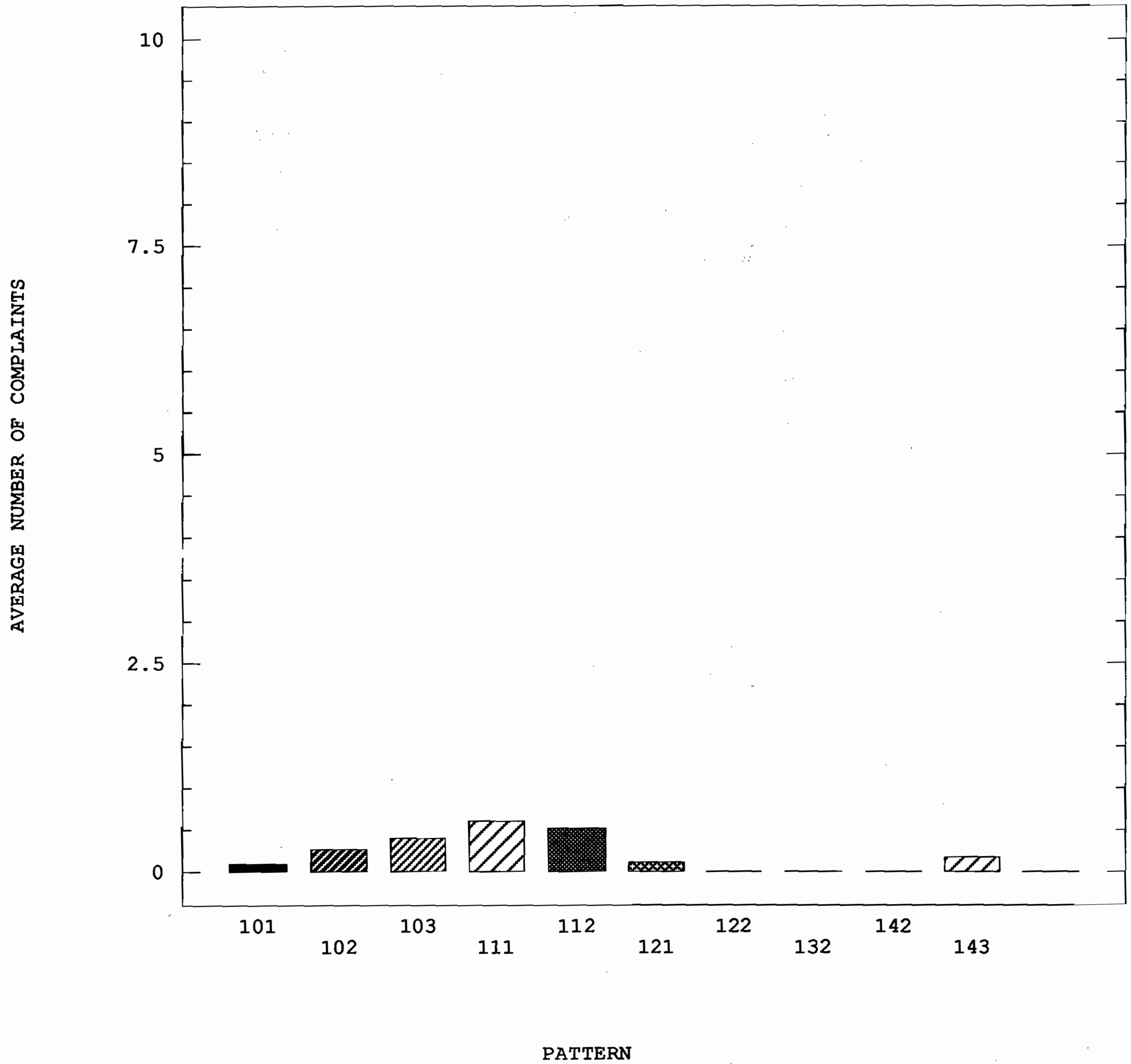

FIGURE 15
AVERAGE COMPLAINTS PER
CAST BLAST PATTERN

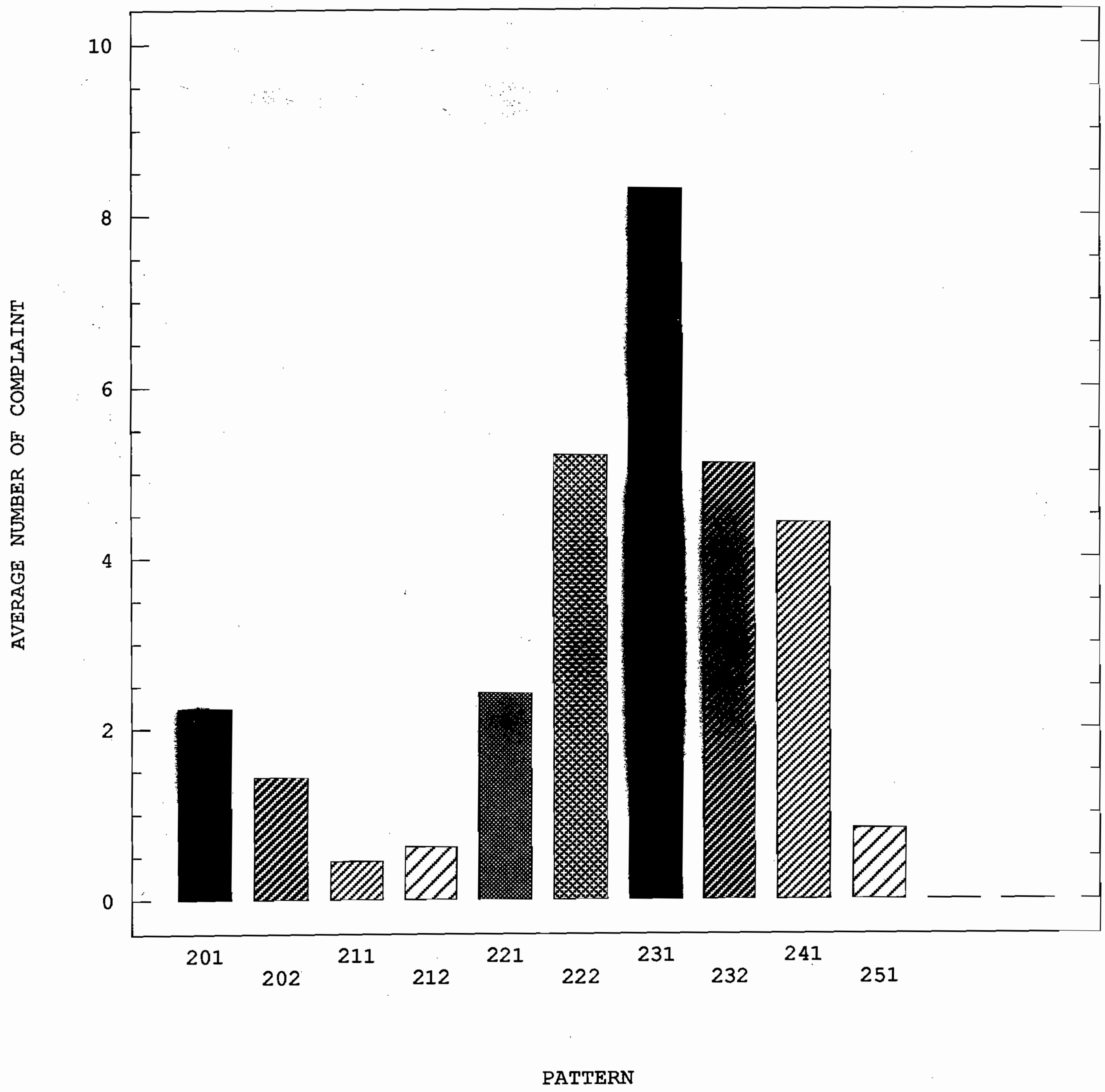

FIGURE 16

TIME DISTRIBUTION OF 100 AND 200 BLAST PATTERNS

JANUARY 1988 THROUGH APRIL 1992

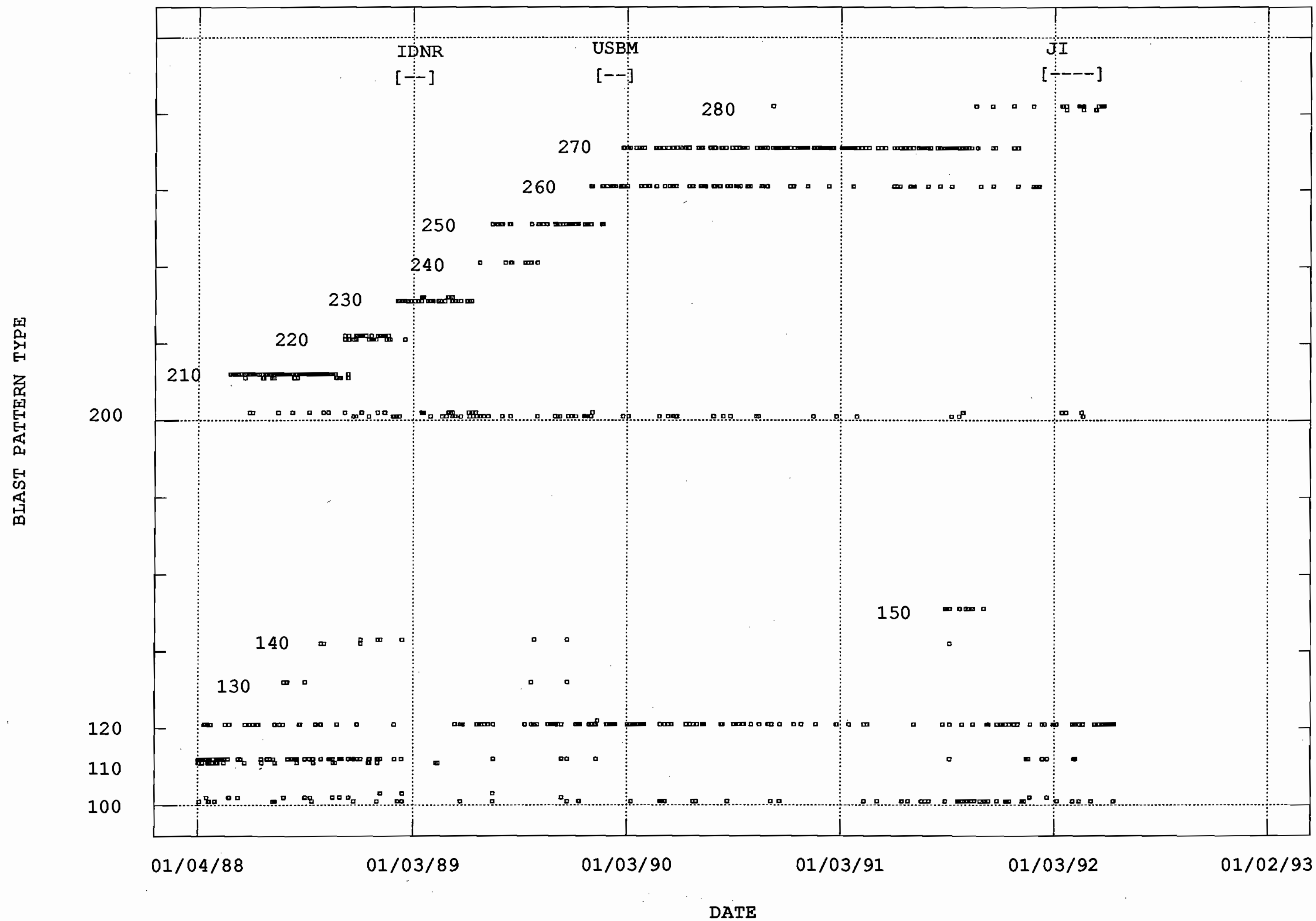

FIGURE 28

COMPLIANCE STATION DATA

CAST BLAST PATTERN 210

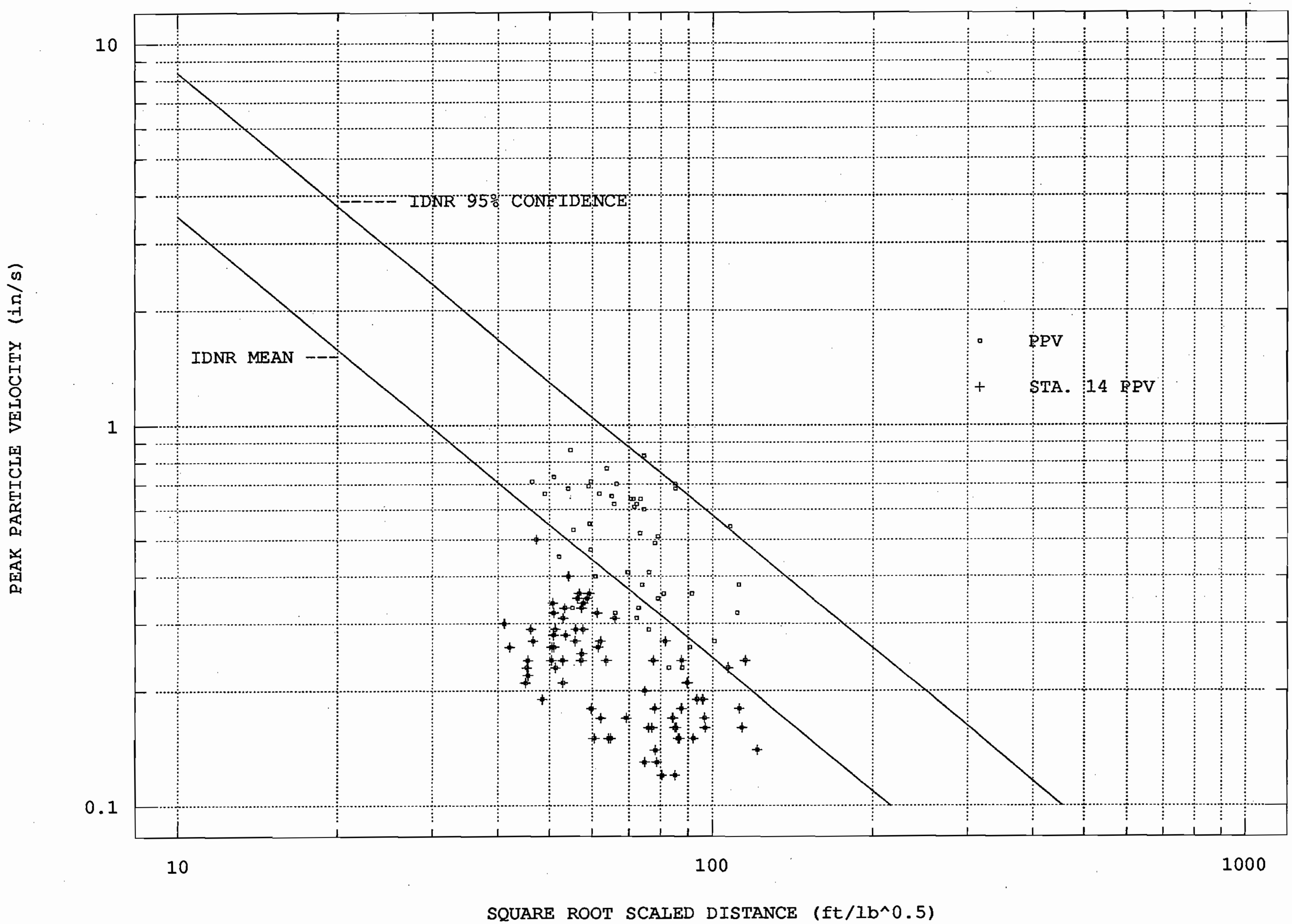

FIGURE 27

COMPLIANCE STATION DATA

CONVENTIONAL BLASTS (SERIES 100)

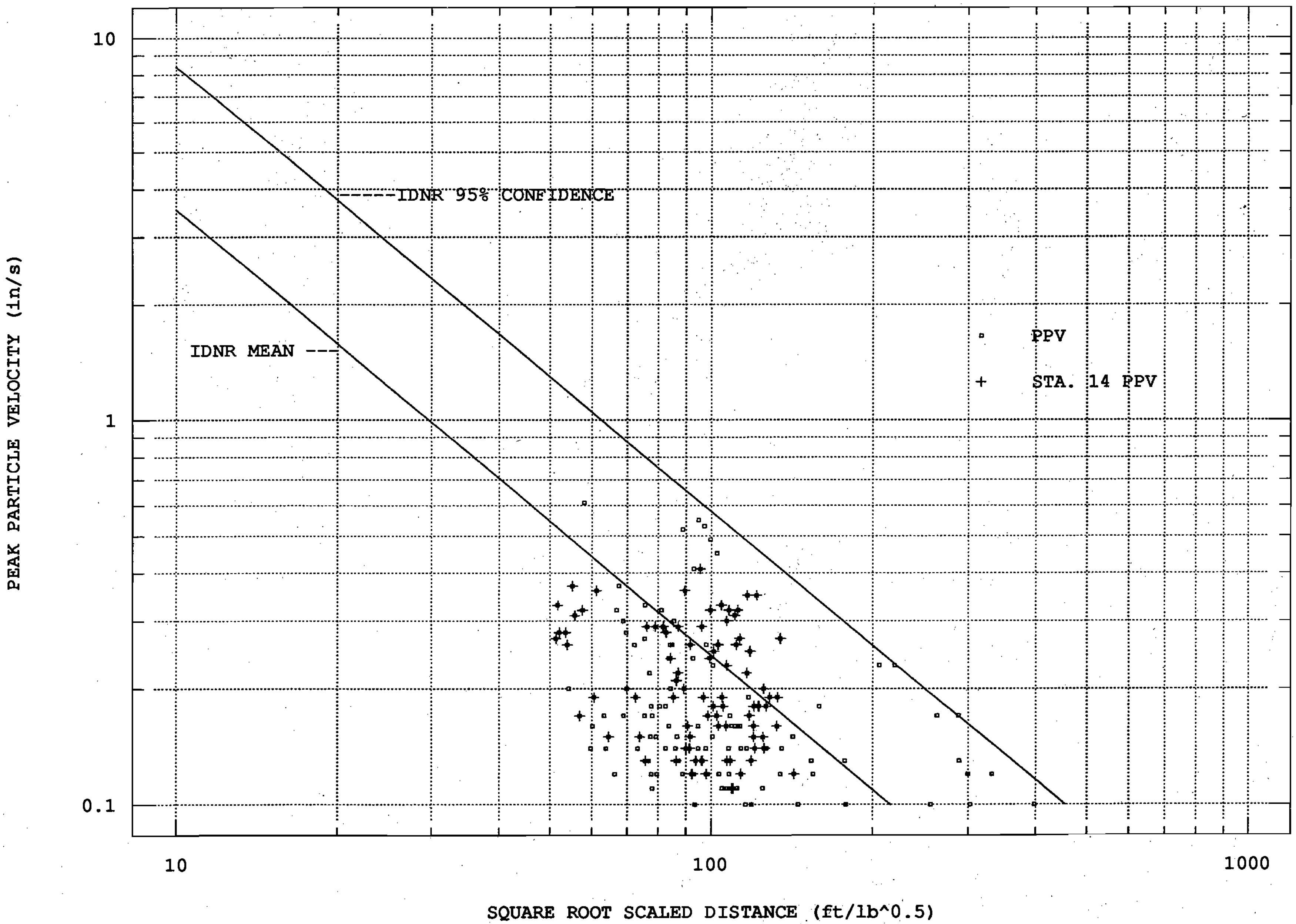

FIGURE 26

COMPLIANCE STATION DATA

JANUARY 1988 THROUGH 1992

CAST BLASTS EXCEPT FOR STATION 14

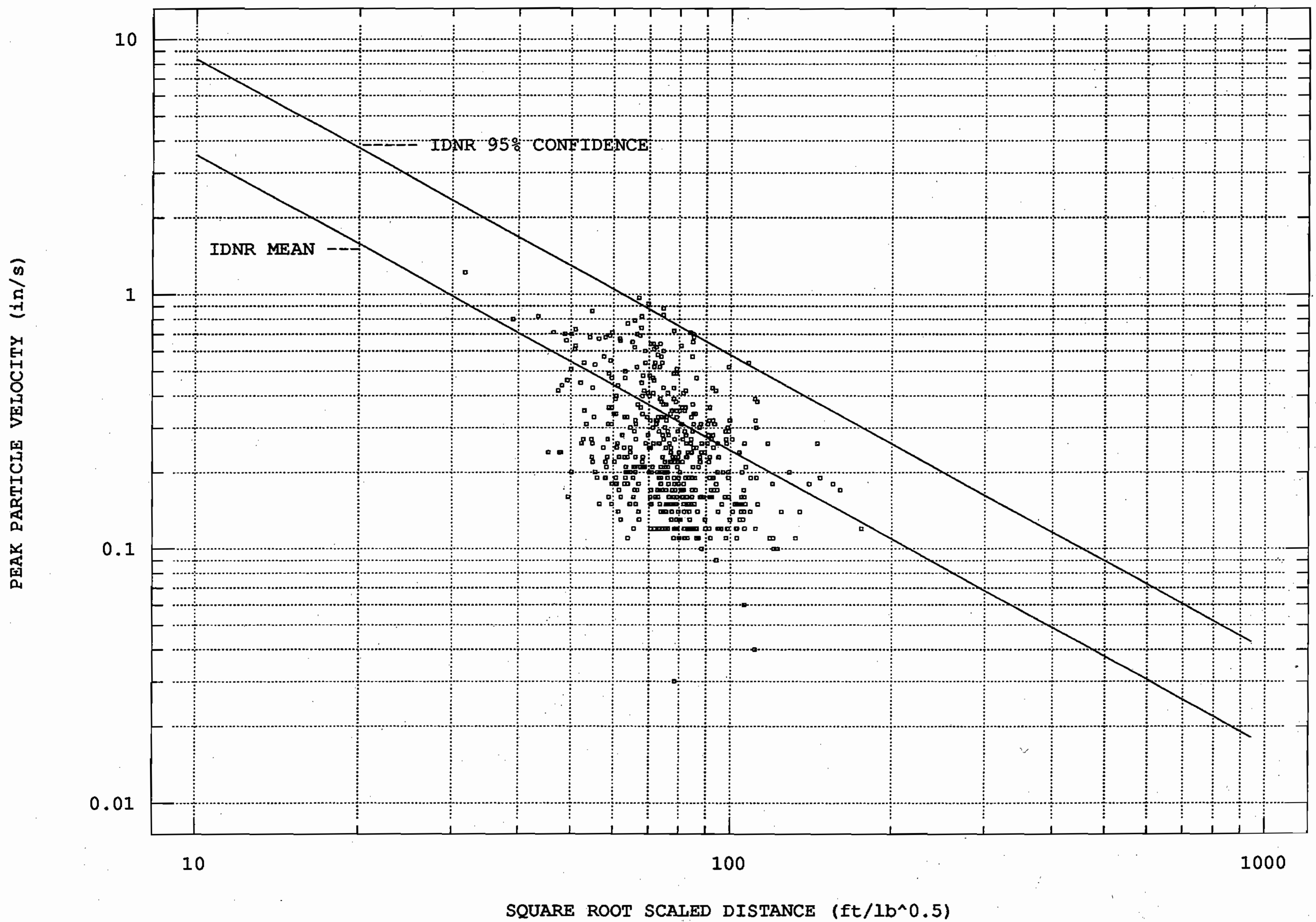

FIGURE 25

COMPLIANCE STATION DATA

JANUARY 1988 THROUGH APRIL 1992

CONVENTIONAL AND CAST BLASTS EXCEPT STATION 14

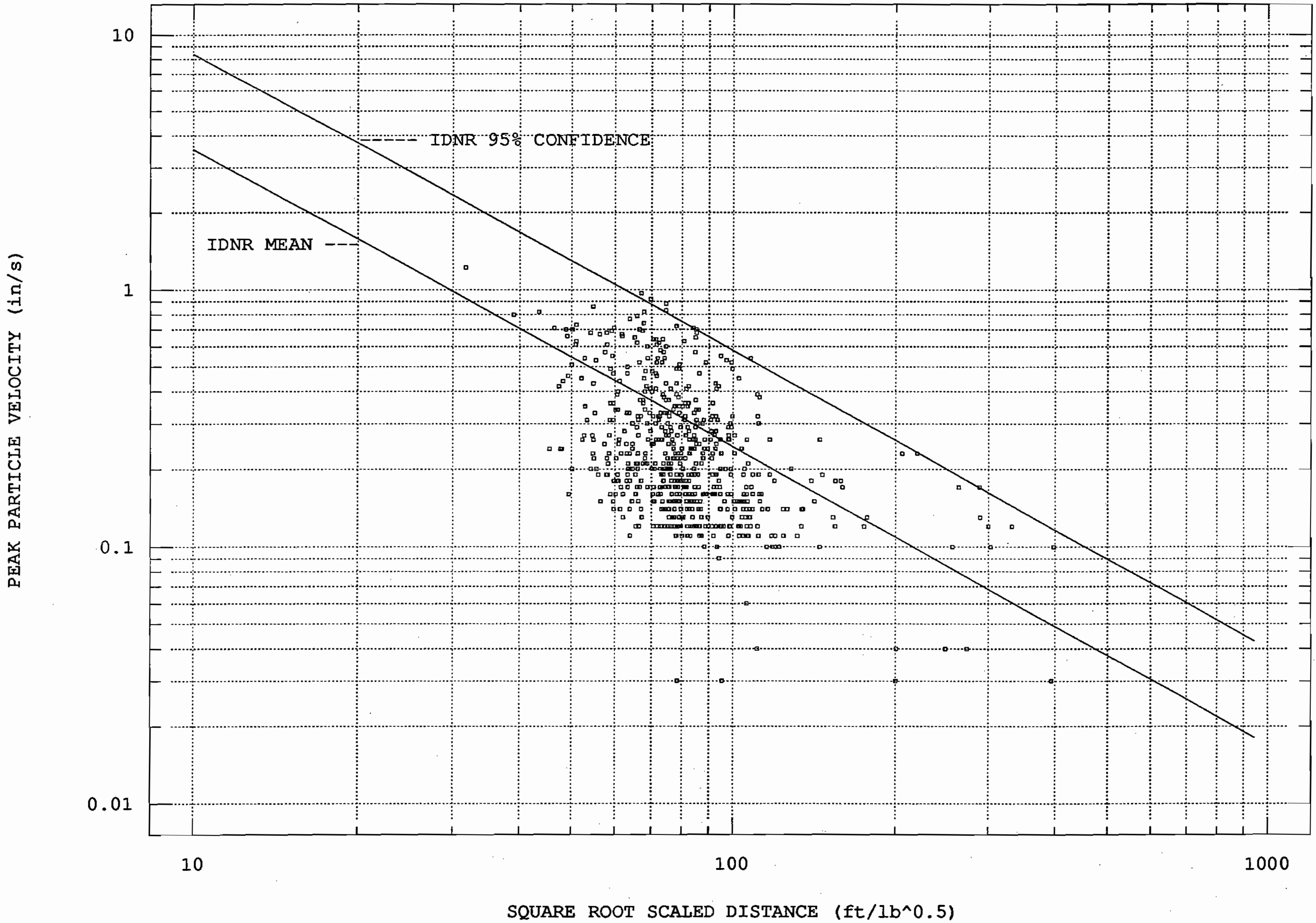

FIGURE 36

COMPLIANCE STATION DATA

CAST BLAST PATTERN 200

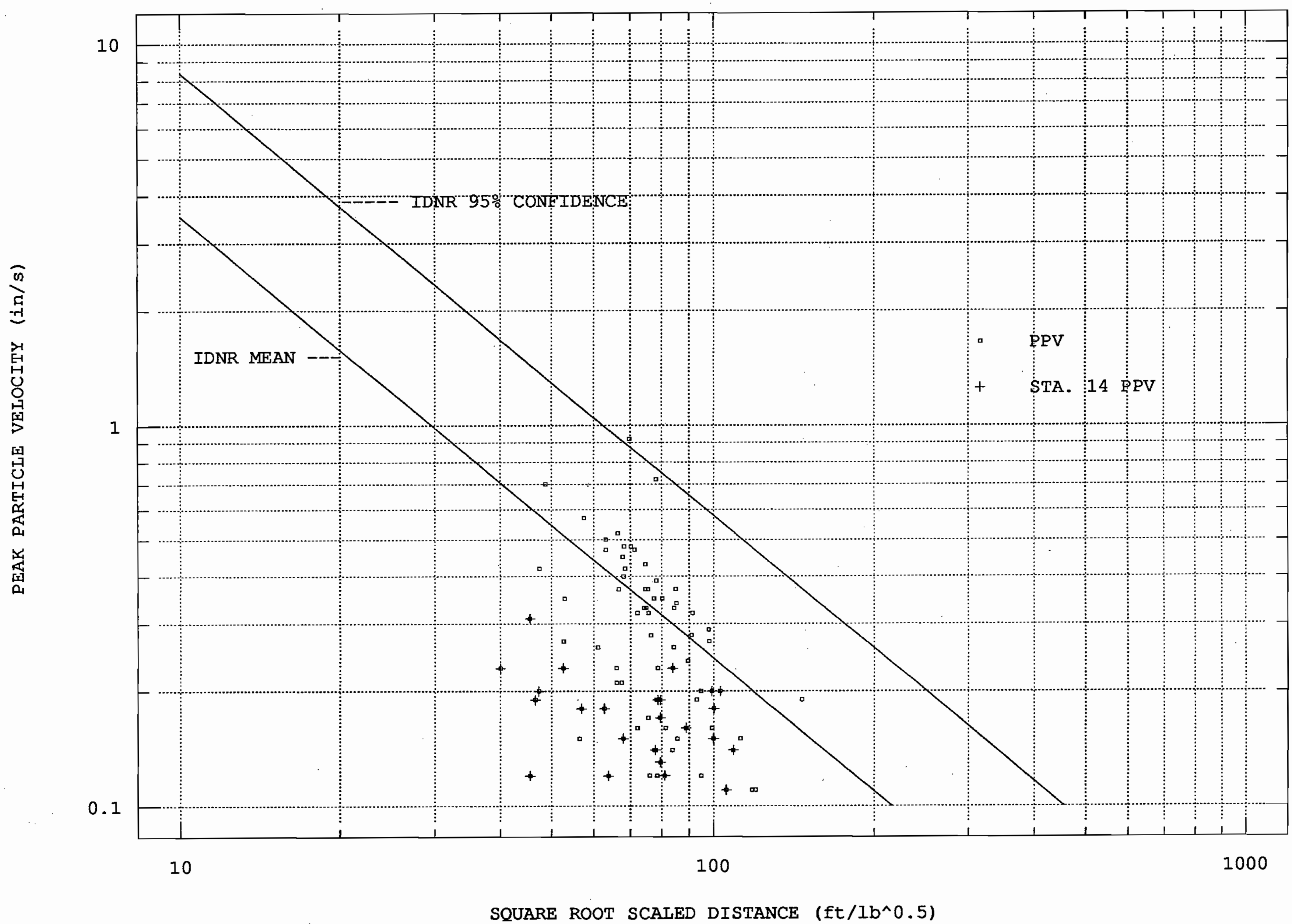

FIGURE 35

COMPLIANCE STATION DATA

CAST BLAST PATTERN 280

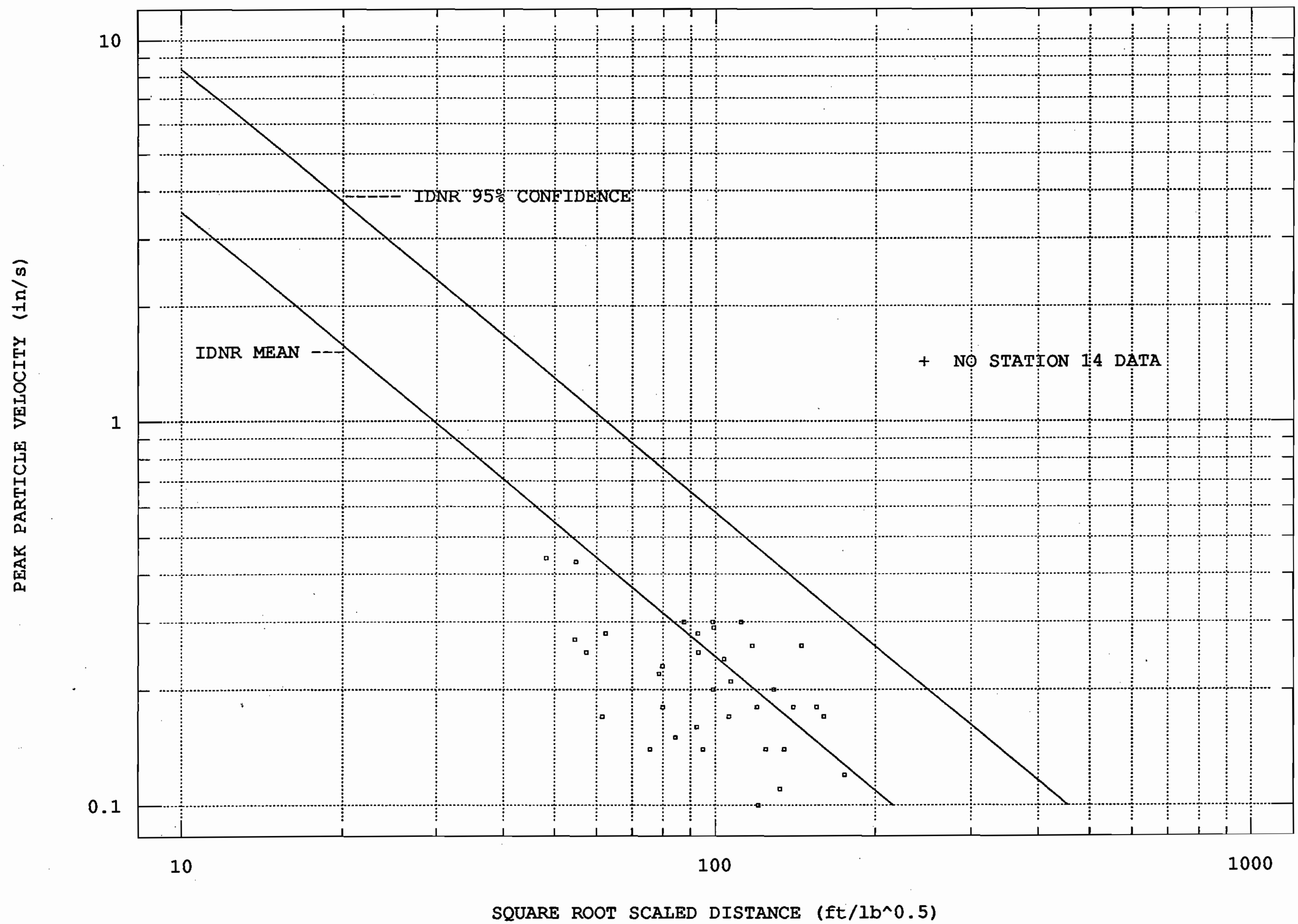

FIGURE 34

COMPLIANCE STATION DATA

CAST BLAST PATTERN 270

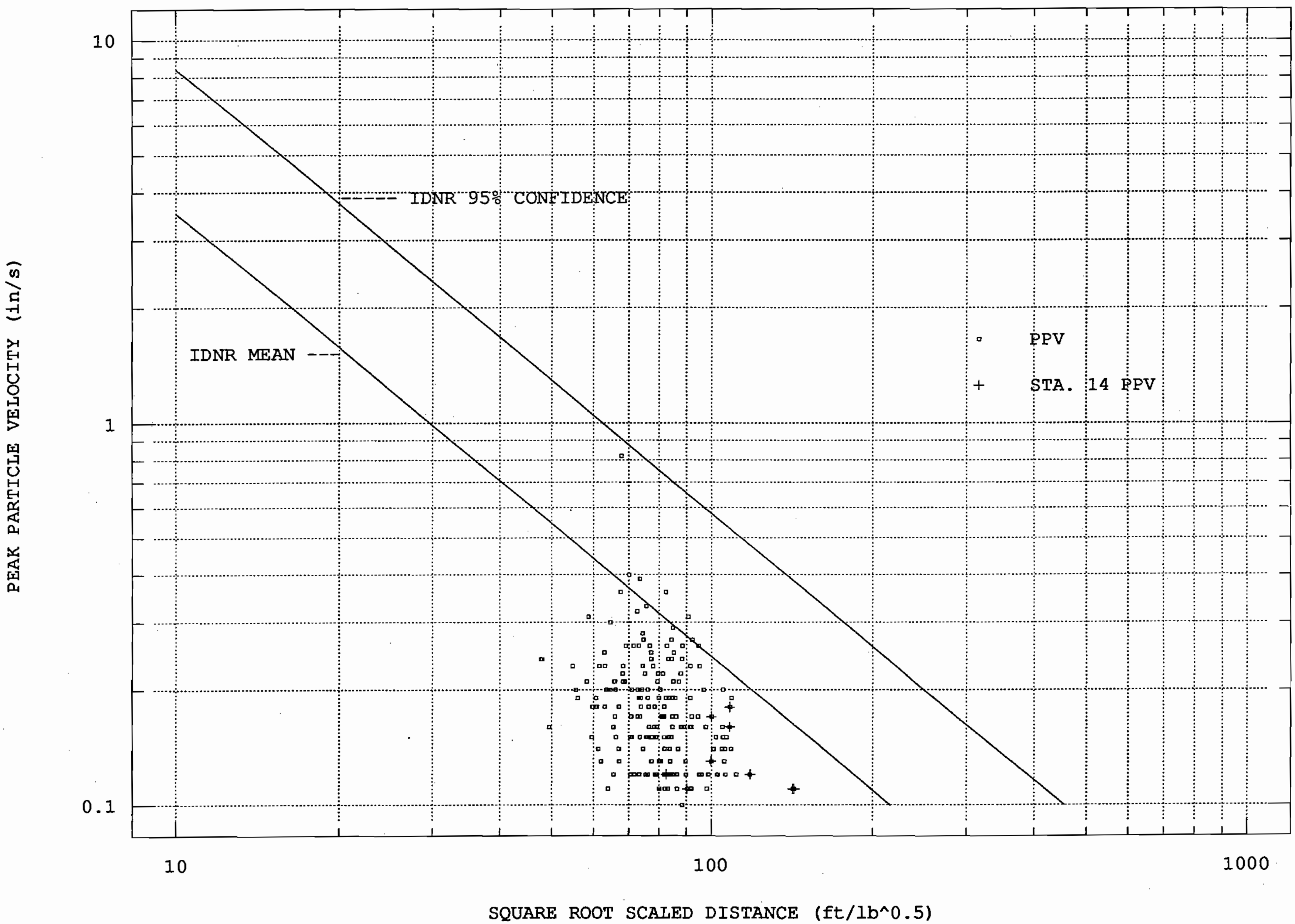

FIGURE 33

COMPLIANCE STATION DATA

CAST BLAST PATTERN 260

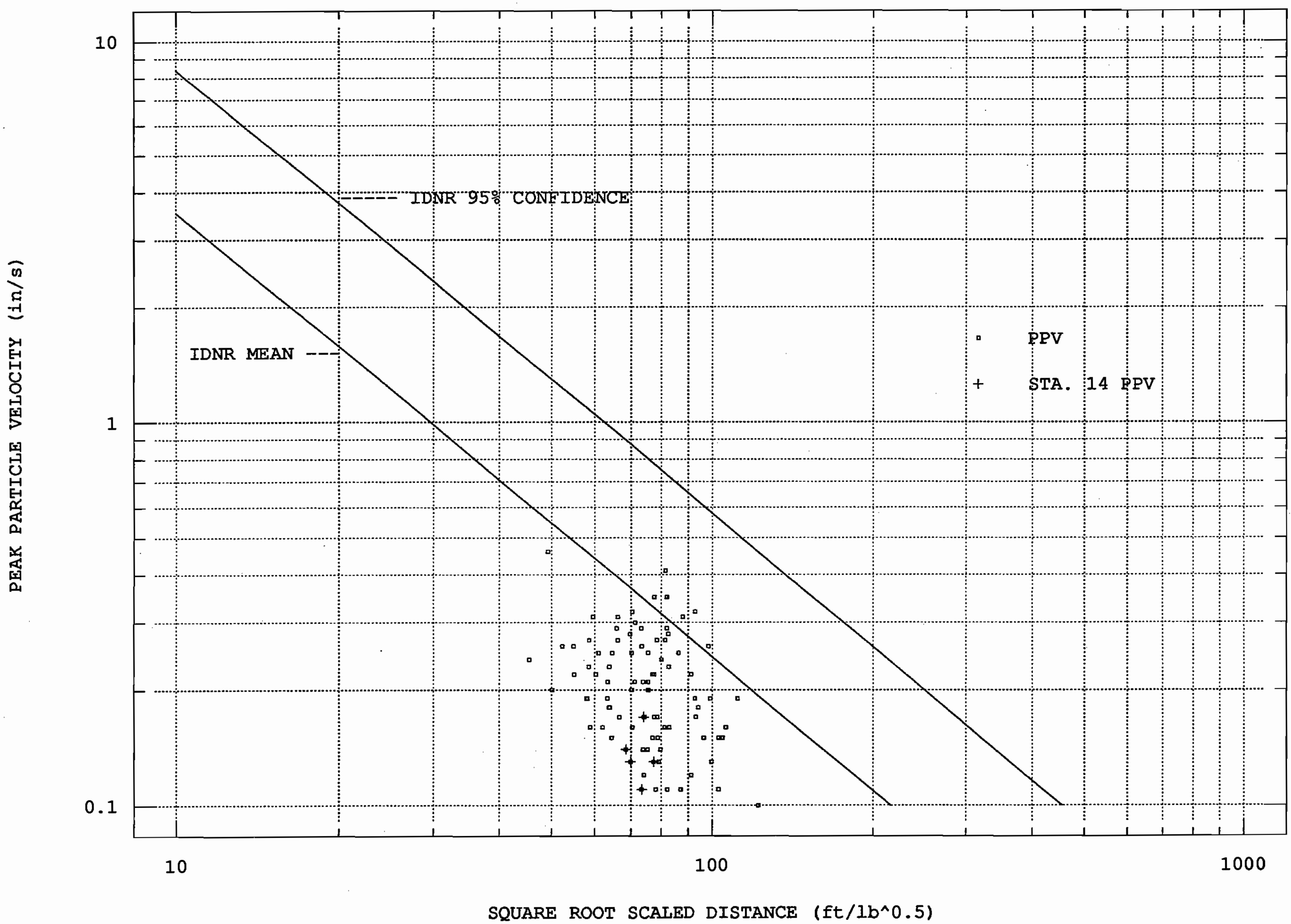

FIGURE 32

COMPLIANCE STATION DATA

CAST BLAST PATTERN 250

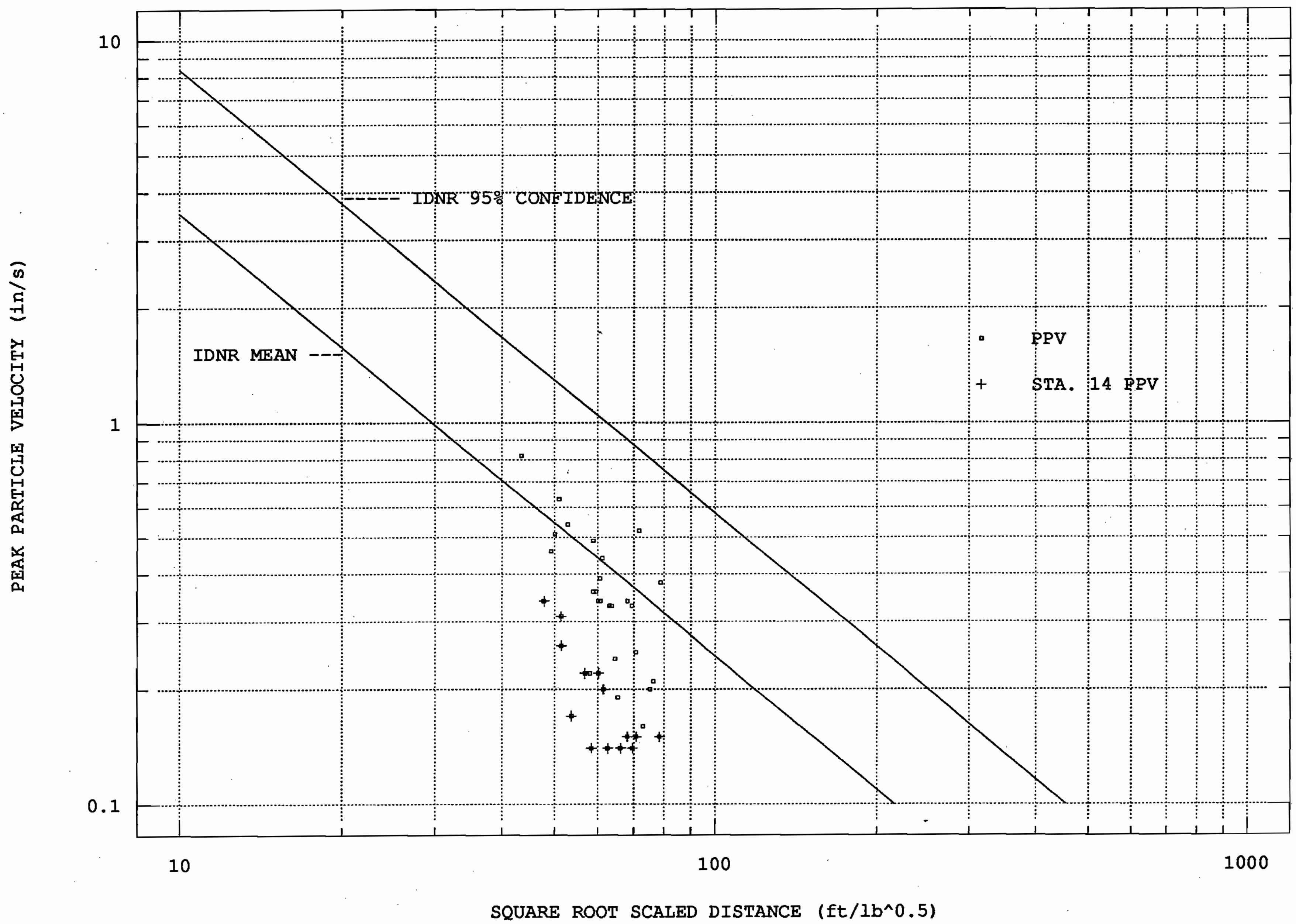

FIGURE 31

COMPLIANCE STATION DATA

CAST BLAST PATTERN 240