In a conventional quarry blast, gas pressure is immediately relieved through the top of the shot, greatly increasing the potential for airblast and flyrock. A power deck shot, on the other hand, utilizes a plug to direct the force downwards and breaks the rock with tension, rather than compression. When a bottom-hole power deck is combined with top and/or middle decks, dramatic increases in control and reductions in vibration are possible. Typically, stemming length can be reduced without increasing the danger of blowout, thereby allowing much better fragmentation in the collar area, and vibrations can be cut down to as much as one-fifth of their original magnitude.

Blasting Analysis International Inc. (BAI), an independent international blasting consultancy group, were recently commissioned to carry out an independent test of the Power Plug (a device used to create power decks) in full-scale blast environments. The purpose of this exercise was to provide a quantitative evaluation of power deck blasting techniques against full-column explosive loads, with direct comparisons for fragmentation, ground vibrations, sub-grade drilling and the degree of rock pile displacement (throw).

**FULL-SCALE TESTS**
Two full-scale test series comprising single-hole characterization tests and full-scale blasts were conducted at two US limestone quarries, one in Kentucky and the other in Pennsylvania. Both sites utilized 159mm diameter blastholes with bench heights ranging from 14–16m and with 0.9–1.2m of sub-grade. Drilling patterns averaged 3.7m x 4.3m.

With reference to figures 1 and 2, the single-hole characterization tests consisted of:
- **Normal hole** — a full column of explosive in a 15.8m deep hole with 0.9m of sub-grade and 3.7m of stemming.
- **Single power deck hole** — a 0.9m air-deck at the bottom of a 13.7m deep hole with 3.7m of stemming and no sub-grade.
- **Double power deck hole** — a 0.9m air-deck at the bottom of a 15.8m deep hole with another 0.9m air-deck in the middle of the column of explosive and 3.7m of stemming.

The single-hole characterization tests were used to:
- Establish control measures
- Check and verify each explosive system
- Verify the functioning and reliability of the Power Plug
- Measure the VOD of the explosive and the resulting gas-front velocity in the air-decks.

Two full-scale shots comprising 30 holes each were evaluated, as illustrated in figure 3. Everything in the blast designs remained constant for each shot, except that one of the shots used the power deck technique with a 0.9m air-deck at the bottom of each hole, while the other was loaded full column. The full-column load is referred to in this report as the ‘normal’ shot and the bottom-hole air-deck shot is referred to as the ‘power deck’ shot.

**INSTRUMENTATION USED**
A number of state-of-the-art blast-monitoring instruments were used on all of the single-hole and full-scale shots for quantitative analyses. All of the test shots were monitored and analyzed by BAI.

**Borehole inspection camera**
Each monitored test hole was probed and recorded using a borehole inspection system. The main purpose of each borehole was to ensure the...
integrity and consistency of the rock, as factors such as major faults, discontinuities and voids, could drastically alter the results. The borehole inspections were also a good way of verifying any major changes in the structural geology within the borehole and blast block. Any test boreholes which differed drastically from the other comparison holes were discarded and new holes were drilled. Also, all single-hole tests were spaced at least 15m apart from one another to ensure that the rock mass would not be affected by adjacent detonations.

Conventional and laser surveying systems

Both conventional and laser surveying were used on each test shot/blast set-up. Conventional surveying was used to line up the small 76mm diameter horizontal hole (see figs. 1 and 2) so that it would intersect the 159mm diameter vertical face hole. This was accomplished by setting up a theodolite on the floor of the quarry and shooting the center of a plumbed survey rod placed over the center of the vertical hole.

A vertical line was then brought down to the toe close to the floor level and a collar point was established. Because it was difficult to establish a collar point on the face at the exact floor level, the smaller intersecting hole was actually started 0.6–0.9m above the floor. Trigonometric calculations were performed to ensure that the hole broke through to the bottom of the vertical hole, given the toe burden, hole depth, slope distance and height of the collar point above the floor elevation.

Laser surveying was performed to establish the true burdens along the bench face from the crest to the toe. This was necessary in order to normalize the data results, since the burdens in some areas along the face varied by up to 1.2m. Laser surveying was also used to establish the location of markers on the face relative to the hole, bench height and true burdens. These markers were used in conjunction with a high-speed video camera for tracking purposes.

High-speed video and film cameras

High-speed video cameras, high-speed 16mm film cameras and standard digital camcorders were used on each test shot to quantify the shot dynamics, throw and delay timing. In order to analyze the full-scale blast accurately, both dimensional and time controls were established for each test shot.

For 2-D analysis, a minimum of four control points, with known co-ordinates, forming a distinct quadrilateral must be available in the field of view (fig. 4). This allows the calculation of eight calibration constants with a system of linear equations in eight unknowns. These calibration constants correct for the vertical, horizontal and elevation co-ordinates of the camera’s location in relation to the test location. They automatically adjust for the zoom focal length, lens aberration and screen curvature; correct for motion towards or away from the optic axis; and accommodate any vibration in the recorded field of view.

The analytical software used for this was MotionTracker-2D, which was developed by BAI.

Each face marker used for tracking purposes was hung over the face on a separate line. All the lines were bunched together and wrapped around a surface detonator with the same firing time as the in-hole delay. When the hole is detonated, all the lines are cut simultaneously, so that during motion the markers move freely and not as a pendulum with one end fixed.
resistance wire or fibre-optic-based VOD systems, the TDR based VODR-1 system was selected for its reliability and flexibility in obtaining field measurements.

The most critical measurements were in determining the velocity of the Power Plug and the gas front travelling through the bottom and mid-column air-decks. For this purpose, one of the VODR-1 systems used only the FSJ1-50A coaxial cable. This is a special foam dielectric coaxial cable with a low crush hold that can measure any disturbance front in a borehole down to a value as low as 100m/s.

By measuring the velocity of the Power Plug and the mass of stemming on top of it, the kinetic energy impacting the bottom of the hole could be reliably and easily calculated.

**Seismograph instrumentation**

Vibration/airblast measurements were obtained using four-channel, full-waveform, digital seismographs. A linear seismic array comprising five seismographs was placed behind each test shot at distances varying from 30–600m (fig. 7). This was necessary to establish the site-specific attenuation characteristics of the vibration and airblast from the single-hole and full-scale blasts. It was also very important for single-hole signature analysis when coupling air-decks with precise electronic detonators.

Once the seismic data had been analyzed, they were normalized in order to compare the normal shot with the power deck shot.

**Fragmentation analysis**

Digital fragmentation analysis was performed on both full-scale shots using Split-Desktop software. Around 32–36 digital images were taken of each rock pile to ensure statistical significance when comparing the results of the normal shot with the power deck shot.

Despite what all fragmentation analysis software developers claim regarding the accuracy of their software, digital fragmentation analysis can be highly subjective unless extreme measures are taken to keep the analysis parameters consistent, particularly in the sampling technique. If this is not done properly, the analysis can easily be skewed to generate any desired results.

Thus, in this series of tests, a great deal of detailed planning and testing was undertaken to minimize or eliminate the inherent cumulative errors. For each rock pile the following analytical procedures were implemented to ensure consistency.

Oversize generally results from the stemming area and ends up on top of the rock pile. The thickness of the oversize, with reference to a cross-sectional dig of the entire rock pile, was approximately 25%. Thus, 25% of the rock-pile images were taken from the top of the pile and the remaining 75% were taken over four cross-sectional digs throughout the rock pile from the beginning to the end of the digging cycle (see fig. 8).

Extreme care was taken to avoid duplicating the rock images, particularly along the top of...
During digging it was inevitable that some of the oversize material from the top of the pile would roll down and collect on the floor. Thus, all of the cross-sectional images were strategically collected to avoid any duplication in the counting of the oversize rocks (fig. 9).

Prior to any of the fragmentation analyses, tests were conducted on a number of known but different fragment sizes of the processed rock, the purpose of which was to determine the optimum dimensional control needed to measure the rock fragmentation of interest in the rock pile.

Based on these fragmentation calibration tests, it was determined that the length/width of each image should be somewhere between five to 12 times the size of the dimensional controls (disc size).

Given this criterion, the field of view per image was limited to approximately 2.0–5.5 m. This approach worked very well for the expected rock size distribution. An example of this sampling technique is illustrated in figure 10 and the accompanying rock size is shown in figure 11.

Another factor that had to be considered before any of the fragmentation measurements could be made was the effect of shadows on the rock. To minimize this error, all digital images of the rock piles were taken at the same time of day, between 3.00 pm and 4.00 pm.

Once all the individual rock images had been analyzed, they were merged together to develop a histogram and cumulative percent passing curve for the entire rock pile.

**TEST RESULTS**

The main test results focused on the two full-scale shots—normal versus the power deck. Once the data had been analyzed, direct comparisons could be performed for the fragmentation, vibration, and rock pile throw.

**Fragmentation results**

The fragmentation results are presented in the form of cumulative percent passing and histogram curves. The cumulative percent passing curves for the normal shot and the power deck shot are illustrated in figures 12 and 13 respectively. The histograms for the normal shot and the power deck shot are illustrated in figures 14 and 15. The numerical results from the graph comparisons are summarized in table 1.

The most significant difference in the fragment size distribution was found in the P20, P50, and P80 passing sizes. In all cases, the power deck shot resulted in a fragment size reduction of approximately 24% for the P20 passing size, 25% for the P50 passing size and 21% for the P80 passing size. Thus, the fragment size distribution was substantially reduced in the power deck blast. No significant differences were found in either...
blast for the smaller size range below 50–75mm or the top size at 600–650mm.

**Ground vibration results**
Ground vibration results comparing the normal and power deck shots are illustrated in figure 16 as a plot of particle velocity versus scaled distance. Scaled distance is defined as the distance divided by the square root of the maximum amount of explosives per delay. This plot is a very good way to normalize the data for comparison purposes, as the distances from the test shots to the seismograph locations and the maximum weight of the explosives varied. Vibration amplitudes were reduced by an average of 33% for all locations, given a distance and maximum weight of explosives per delay. A 33% reduction in the amplitudes is significant in view of the attenuation characteristics over distance. Also, the power deck blast did not trigger the seismograph which was stationed farthest from the shot, while the normal blast did.

**Power plug velocities through bottom-hole air-deck**
The Power Plug velocities travelling through the bottom-hole air-deck were measured in each test hole as previously illustrated in figures 1 and 3. As far as is known, this is the first time that the Power Plug velocity travelling through a bottom-hole air-deck has been measured successfully. Velocities varied from around 300 to 3,400 m/s depending on the type of explosive, the amount of stemming mass placed on top of the Power Plug, and the confining conditions of the hole.

<table>
<thead>
<tr>
<th>Table 1: Numerical results from graph comparisons</th>
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<tbody>
<tr>
<td>Normal Shot</td>
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<tr>
<td>------------------</td>
</tr>
<tr>
<td>No. of combined images</td>
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<tr>
<td>Minimum size measured, mm</td>
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<tr>
<td>P20 size, mm</td>
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<td>P80 size, mm</td>
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<tr>
<td>Top size measured, mm</td>
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surrounding rock mass.

The gas-front velocity travelling through the small 76mm intersecting hole varied from around 250m/s to just over 600m/s. Figure 17 illustrates an unfiltered displacement versus time plot of the Power Plug velocity in the 159mm diameter vertical hole and the gas-front velocity travelling through the small intersecting face hole. This was the highest Power Plug velocity recorded to date in 127–165mm diameter blastholes with a 0.9m bottom-hole air-deck. The explosive column VOD ranged from approximately 4,000 to 4,600m/s.

**Rock pile displacement**

The rock pile shapes and cast distances were measured for both the normal and power deck shots. The comparison results are illustrated in figure 18. The normal shot spread the rock pile over a distance of 90m and the power deck shot spread it over a distance of 85m, thus there was no significant difference between the two shots.

The centers of gravity of the rock piles were the same at around 23–30m, and although the rock pile profiles varied slightly, the maximum height of each pile was roughly the same.

**CONCLUSIONS**

The following conclusions have been reached about the power deck tests:

1. Full-scale shots were evaluated with sophisticated blast-monitoring instruments. The normal shot utilized full-column explosives in each hole, and the power deck shot used a 0.9m air-deck at the bottom of each hole. Results were normalized and compared for fragmentation distribution, ground vibration amplitudes and cast distance.

2. With reference to the fragmentation, the power deck shot resulted in a 21–24% reduction over the P20 to P80 passing sizes. The P50 passing size was 124mm for the power deck shot and 166mm for the normal shot. These are significant reductions which can be related to substantially lower costs in terms of primary crusher throughput, wear and tear on the crusher linings and utility costs.

   No significant differences were noted in either shot regarding the smaller fragmentation passing sizes below 50–75mm or the top size 600–650mm.

3. With reference to the vibration amplitudes, the power deck shot resulted in a 33% reduction over all distances in the seismic array line up to about 600m. This is quite significant in reducing complaints, complying with vibration regulations and/or in allowing a mine/quarry to utilize larger shots.

4. The power deck shot resulted in a flat floor equivalent to that of the normal shot. The significance of this is that a properly designed air-deck at the hole bottom, using a Power Plug and appropriate stemming and air-deck length, could eliminate and/or reduce all sub-grade drilling. This results in a direct drilling and explosives cost saving, without affecting the overall blast results.

5. No significant differences were found in the rock pile shape, center of gravity or cast (throw) in either blast; both the power deck shot and the normal shot produced similar results.

Bottom-hole and multiple power decks can offer significant benefits to quarry operations by lowering the powder factor, eliminating the need for sub-grade drilling and greatly reducing flyrock and vibration, while at the same time maintaining or increasing fragmentation and improving bench floors.