Project Title: **ADVANCED MINING TECHNOLOGIES TO REDUCE UNDERGROUND PRODUCTION COSTS**

ICCI Project Number: 04-1/1.1A-2  
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Project Manager: Dr. Ronald Carty, ICCI

**ABSTRACT**

The Coal Industry professionals have identified improving face productivity and lowering face production cost as a means to accomplish a 20% reduction in production cost of Illinois coal. To achieve this goal, the research in this project focused on improved dust control and reducing OSD as a means to achieve lower production cost.

The dust control research evaluated the sources of dust in the face area from mining and bolting activities. Spatial concentration of dust in an entry being mined was studied which indicated higher dust concentrations near the roof-level and towards the face. Analysis of channel samples from four Illinois mines indicated very high quartz contents in the strata adjoining the coal seam. The dust from these strata was however water-wettable. The wettability of coal seam dust however varied significantly for samples from different mines. A Computational Fluid Dynamics (CFD) model of the continuous miner mining in an entry, with forcing air ventilation was also developed. The results provided valuable insights into the prevalent airflows and recirculation patterns within an entry. This information has the potential to aid development of new concepts to reducing occupational dust exposures in the face area. Based on the study of dust generation and propagation in the face area, a modified continuous miner spray system was designed and tested in the field. The new spray system provided reductions in dust concentrations ranging from 40-60% compared to the currently used spray system. This was accomplished without increasing the total water throughput. An additional innovative concept of "Total Air Filtration" was also developed, tested in the laboratory and demonstrated in the field at two mines. The results from these studies indicated potential for further development of this concept.

The OSD reduction research focused on development of an education program to increase OSD awareness among operators. A sampling study was conducted before and after training of the operators. The results indicated that the education program was successful in reducing OSD by about 1-inch. However, retraining of operators and development of aids to assist the miner operators in controlling OSD became apparent. This led to the conceptual development of a simple technology which can assist the miner operator to minimize OSD.

*Pages 3-7, 19-20 and 43 of this document contain proprietary information*
EXECUTIVE SUMMARY

With funding support from the Illinois Clean Coal Institute and coal mine operators throughout Illinois, and the recommendations of the Coal Industry Research Steering Committee, the authors have been investigating strategies to reduce underground coal production cost in Illinois by 20%. This project (2004-2005) focused on improved dust control and reduced out-of-seam dilution (OSD) as a means to achieve the targeted production cost reduction. A summary of these research activities is provided here.

Task 1: Dust Control

Task 1.1: Spatial evaluation of sources of total and quartz dust in a super-section and bulk analysis of coal and associated strata for quartz.

In this sub-task, dust data was collected around the continuous miner at different heights and distances away from the face as the entry was being mined. The results of this study confirmed the conceptual dust distribution profile developed by the project team that the respirable dust concentrations are the highest at the roof level and decline away from the face. The highest dust concentrations measured were about 57 mg/m$^3$ closest to the face and at the roof level. Away from the face towards the back of the continuous miner and at the mid-plane level the respirable dust concentrations reduced to about 14 mg/m$^3$. These results indicate that efforts need to be focused on controlling the dust at the roof level through the use of appropriate sprays directed in this region. Additional spatial dust distribution data collection focused around the roof-bolter. The results indicated that roof-bolting did not contribute any significant amount of dust to the face operations.

Channel samples of roof and floor strata, and coal samples from three horizons within the seam i.e. top 3-inches, bottom 3-inches and the rest of the coal seam were also collected from four mines in Illinois. Samples were tested for wettability and quartz content. The results indicated that the floor materials were completely water-wettable. The roof materials were also almost water-wettable. The dust from the coal strata however required the use of surfactants to achieve complete wetting within a short period of time. Within the coal seam itself, wettability improved in the layers of coal adjacent to the floor and to a lesser extent, adjacent to the roof. There was also a significant difference in surfactant concentrations required to wet the coal samples from different mines within Illinois. The quartz content analyses of these samples indicated that it was significantly lower in the coal seam than that in the adjoining roof and floor strata. The quartz content in the floor strata was also slightly higher than that in the roof strata.

Task 1.2: Develop and demonstrate concepts for modified sprays on a continuous miner.

Extensive literature review, field observations on dust control in the face area, and conceptual analyses of the efficiency of dust suppression sprays employed on the miner, helped the project team identify several avenues for improving spray efficiency. Three key hypotheses were developed for improving the dust suppression using hydraulic sprays on the continuous miner. These can be summarized as follows.
1. Prevent dust generation, and minimize generated dust from becoming airborne by increasing water at the cutting bits, and cutting face, with appropriate spatial distribution of sprays.
2. Wet and surround the airborne dust to allow the scrubber to capture it.
3. Further wet the airborne dust escaping the scrubber inlets area before it enters the area behind the miner and the last open crosscut.

For each hypothesis, spatial distribution and type of sprays used were different. Due to intellectual property reasons, detailed discussion on the hypotheses and specific spray configurations utilized is not included here.

The redesigned spray system utilized approximately the same number of sprays and utilized the same amount of water as a conventional spray system. This redesigned spray system was tested extensively in the field and compared side-by-side with the conventional spray system. The results indicated that the modified spray design significantly improved dust control in the face area at a statistical significance level of 99.6%. Most typical dust reduction values compared to the conventional spray system varied from 40-50%. The differences in dust exposure to the miner operator and in the immediate return with the modified spray system were determined to be at least 33.6% and 26.9% at 90% statistical confidence. The authors believe that there is margin for even greater improvement with better face ventilation, higher water pressures and further modifications to the spray system.

Task 1.3: Develop a computational fluid dynamics (CFD) model for a single entry in a super-section mining layout in Illinois.

CFD modeling of aerodynamic conditions in the face area has provided invaluable insights into analyzing the problem of occupational dust exposures. Though the modeling needs to be refined further, it is clear that improvements in line-curtain management practices are necessary to reduce dust exposures to the occupations operating in the face area and to dilute methane concentrations at the face. Based on the current research the following broad conclusions can be made.

- The recirculation behind the line-curtain increases the dust exposure of ram-car operators. The recirculation reduces as the distance between the end of the line-curtain and the miner increases. Also, the presence of leakage paths over the top of the line-curtain reduces recirculation. Hence, the exposure of ram-car operators in the face area can be minimized by better curtain handling practices and through ideas such as introducing leakage paths in the center of the curtain at the ram-car operator breathing level.
- It is clear from all the models that the line-curtain air reaching the face is limited. This is unfavorable from methane dilution point of view but can be used to an advantage for improved dust control. Lower air quantity at the face helps in containing and concentrating the dust close to the face where no occupations operate. Hence, effective use of hydraulic sprays and directing the face air into the scrubber can achieve a good degree of dust suppression. Also increasing water spray pressure may have a detrimental effect on dust control in the face area.
• Line-curtain leakages at the floor level eliminate recirculation at the floor level. However, since the breathing zones for all occupations are either at the mid-plane level or in between the mid-plane to roof level, leakages at the floor level should be minimized to the extent possible.
• Slab cuts appear to be less dusty, particularly for the ram-car operator due to absence of any recirculations in the entry.

Task 1.4: Development of low-cost additional control devices for total and quartz dust control.

In this task, a "Total Air Filtration" concept was devised, tested in the laboratory and demonstrated in the field. This concept utilized filter panels which could be stretched across the cross-section of the entry at a suitable location away from the paths of mine equipment and also allowed for passage of personnel through an opening or a doorway within the filter panel.

Nine filter materials were tested in the SIU-Joy scrubber efficiency laboratory which achieved dust capture efficiencies from 9% to 89%. However, high capture efficiencies were associated with higher pressure drops across the filter material. Hence, to achieve a balance between capture efficiency and resistance to air flow, two filter materials were selected for additional field testing. During field testing these materials provided respirable dust reductions from 2.53 mg/m$^3$ to 2.19 mg/m$^3$ and 2.23 mg/m$^3$ to 1.96 mg/m$^3$. The capture efficiencies could have been much higher, albeit at an increased pressure drop, if the tests would have been run for a duration longer than 60 minutes as was done in these tests. During the duration of the tests, a moderate drop in air velocities was observed in the entry after introduction of these filters. The project team however believes that these issues can be resolved effectively through proper installation of pull-thru curtains, changes in regulator openings and appropriate simulations of mine ventilation within a panel. Studies also indicated that the filter panel life could easily be matched to one shift duration making their application more practical.

Additional tests on the low-cost filter panel for dust control were conducted at a Central Illinois mine. These tests were conducted in the production shaft hack belt area. The results indicated that the filter panel, when used in conjunction with water sprays, was the most effective measure for controlling the dust. Downstream dust concentrations as measured by the personal data rams were reduced from 14.5 mg/m$^3$ to 5.3 mg/m$^3$ with the use of the filter panels.

To determine the permissibility of the filter material for underground use, the MSDS information on the filter materials was forwarded to MSHA. After preliminary evaluation, the material did not appear to present any major issues for underground use. However, it was concluded that to obtain the final permissibility approval, laboratory studies on flammability and combustion gases analyses by MSHA would be required.
Task 1.5: Provide technical support to coal mines to improve dust control to meet MSHA standards.

Over the course of the project performance, the project team entertained requests from mines and referrals from MSHA to provide assistance to three mines in Illinois with respect to dust control issues at the face and elsewhere underground. The project team conducted investigation of the problem, conducted laboratory tests to develop solutions and proposed a list of recommendations for implementation at the mines. At a Central Illinois mine, the project team recommendations in dealing with dust control in their materials handling shaft were implemented which led to a 50% reduction in dust. There were additional requests for technical support which could not be fulfilled due to budgetary constraints which provided funds for this activity at only two mines.

Task 2: Developing an Education Program for Reducing Out-of-Seam Dilution

Task 2.1: Detailed study of OSD at one mine.

A detailed OSD study was conducted at a Central Illinois mine. A baseline study benchmarked existing OSD levels at one unit in the mine. Using the benchmarked current practice data, an education program was prepared in concert with the mine professionals and achievable goals were established. The mine management delivered the education program to the operators. The education program was immediately followed by a study to gauge the impact of the education program and quantify the reduced dilution as a result. The study findings can be summarized as:

- The education program did have a positive impact. A decrease of 1-inch in the mining height was documented after the education program.
- Immediately after the education program, mining height reduction was ~1.5-inch. Two weeks after that, mining height drifted back to the pre-education program levels. This emphasizes a continued need for monitoring and retraining the operators.
- As conscious efforts were made by miners to reduce dilution, reduction in roof dilution was achieved at some level of significance. This is despite the fact that the roof dilution was already low.
- The inability to effectively control floor dilution is attributed largely to the fact that it is very difficult for the miner operator to detect the transition of the cutting head from coal to the floor. This emphasizes the importance of developing interface detection and simplistic automated mining height control technologies.

Task 2.2: Develop simple low-cost concepts to minimize OSD in collaboration with Joy Mining Machinery.

The OSD study conducted at the Central Illinois mine revealed the necessity of developing a system which will allow the miner operator to identify the interface/transition from the coal seam to the floor. Hence a simple technology was conceptualized that could be readily implemented on any continuous miner. Detailed discussion of this technology is avoided here for intellectual property reasons.

Pages 3-7, 19-20 and 43 of this document contain proprietary information
OBJECTIVES

The overall goal of this project was to achieve a 20% reduction in production cost of Illinois underground mined coal as identified by the Coal Industry Research Steering Committee, consisting of representatives from most of the active coal companies in Illinois as well as other industry partners. The focus areas investigated in this particular project were Dust Control and Out-of-Seam Dilution. Specific project objectives in these areas were:

i). Reduce dust concentrations with improved productivity for dust compliance with MSHA standards, and,
ii). Improve profitability through out-of-seam dilution control through reduced processing and waste management costs

Towards achieving these objectives, the following tasks were proposed.

Task 1: Dust Control

1. Perform spatial evaluation of sources of total and quartz dust around a continuous miner and roof-bolter and conduct bulk analysis of coal and associated strata for wettability and quartz content.
2. Work collaboratively with Joy Mining Machinery, coal industry professionals, NIOSH and MSHA to develop concepts for modified sprays on continuous miners. Demonstrate in the field selected concepts with highest potential for success.
3. Develop a computational fluid dynamics (CFD) model for a single entry in a typical super-section mining layout in Illinois.
4. Develop low-cost additional control devices for total and quartz dust control that can help the industry in the near-term to meet regulatory requirements for dust control.
5. Provide technical support to coal mines to improve dust control to meet MSHA regulatory requirements.

Task 2: Out-of-Seam Dilution

1. Work cooperatively with a mine to reduce OSD and study its impacts on production and production cost. Use the experience to develop a training program for OSD control in concert with industry.
2. Develop simplified concepts in collaboration with Joy Mining Machinery to modify a continuous miner to control roof and floor cutting and reduce OSD.

INTRODUCTION AND BACKGROUND

Task 1: Dust Control

In the last decade, the amount of coal produced from underground coal mines per employee hour in the United States increased from 2.54 tons to 3.99 tons. These
significant productivity gains have put a strain on mine operators who must comply with the Federal dust standard of 2 mg/m³. For mines already operating at the regulated limit, using new technology to achieve a desired productivity increase usually results in noncompliant dust samples. Furthermore, the results of recent medical studies have led the National Institute for Occupational Safety and Health (NIOSH) to prepare “A Criteria Document for a Recommended Standard for Occupational Exposure to Coal Mine Dust”, which promotes reducing the Federal dust standard to 1 mg/m³. Most operators feel it is just a matter of time before this recommendation becomes the new MSHA standard. If it were to happen today, NIOSH’s Division of Standards Development and Technology Transfer estimate that only 37% of the mining units in the country would be in compliance. Now that the push for productivity has so many mines operating at or over the allowable limit for respirable dust, optimizing existing dust control systems and finding new ones has become a top priority. Towards that end, SIU and Joy Mining Machinery have collaborated to develop improved wet-scrubber designs and modified spray systems based on conceptual dust profiling in the face area. These modifications have been tested in the field to provide improvements in visibility and respirable and quartz dust concentrations. These findings have been verified by independent sampling by the mine and MSHA.

In the present project, more accurate quantitative dust profiling in the face area and CFD modeling have led to a vastly improved spray design which has been demonstrated in the field. Additional low-cost auxiliary dust control devices such as filter panels in entries have also been evaluated in field testing. These devices offer a significant promise but require more detailed investigations and approvals by regulatory agencies.

**Task 2: Out-of-Seam Dilution**

Over the past two decades, manufacturers continue to develop higher production methods and equipment. These have led to lower production costs enabling the industry to remain competitive. While productivity has risen dramatically, the quality of product mined at the face has steadily declined. Beyond mining lower quality seams, it is also true that the mines are removing a higher percentage of out-of-seam materials (roof and floor) than before, and the push for higher production levels has caused operations to lose focus on the quality of the mined material. Average recovery of marketable coal today in Illinois is about 65%. The remainder waste must be suitably disposed. Studies by SIU in previous projects have indicated that dilution control has potential to decrease production cost by 5-10% with minimal effort. To further advance the Out-of-Seam dilution control area, this project involved development of an education program as a tool to reduce OSD through creating awareness among the miner operators and face personnel. The education program was preceded and followed by an extensive sampling program to quantify the success of the education program by itself in controlling OSD. Based on the findings of this study, supplementary low-cost aids to assist the miner operators in maintaining a proper horizon have been conceptualized. Their feasibility has been supported by the mining company professionals.
EXPERIMENTAL PROCEDURES AND MODEL DEVELOPMENT

Task 1: Dust Control

Task 1.1: Spatial evaluation of sources of total and quartz dust in a super-section and bulk analysis of coal and associated strata for quartz. The goal of this task was to collect and analyze spatial dust distribution data around important sources of dust generation at the face such as the continuous miner. In addition, the coal seam and adjoining roof and floor strata was to be sampled and analyzed for quartz content and wettability to determine their contributions to dust generation resulting from out-of-seam mining.

The spatial dust sampling study was conducted by sampling respirable dust across the cross-section of the entry being mined using gravimetric dust sampling pumps mounted on the continuous miner at different locations from the face and at different heights. In addition, dust samples were also collected around the roof-bolter during its operation. Channel samples of roof and floor strata, and coal samples from three horizons within the seam i.e. top 3-inch of the coal seam, bottom 3-inch of the coal seam, and the rest of the coal seam were also collected from four mines in Illinois. Samples were crushed, ground, and screened at 500 mesh particle size. Wettability tests were conducted on -500 mesh size fraction using Brady's B/F101 P surfactant. Additionally, the samples were analyzed for quartz content at MSHA Technical Support Center facilities.

Task 1.2: Develop and demonstrate concepts for modified sprays on a continuous miner.

Hypotheses Development

Based on observations of the authors and conceptual analyses of the efficiency of dust suppression sprays employed on the miner, several avenues for improving their efficiency were identified. Three key hypotheses were developed for improving the dust suppression using hydraulic sprays in the face area. These were:

• The primary means of dust control should be preventing the dust generated at the cutting faces from becoming airborne. Flat sprays directed into the bits and the cutting face should achieve this objective and cool the bits.

• Once the dust is airborne, the flooded-bed scrubber is the most efficient mechanism at the face to capture the dust. Hence, the goal should be to maximize the amount of airborne dust that gets directed into the scrubber. To accomplish this, the flat sprays on the boom, help to create a shroud containing the generated dust in a restricted volume. Additional flat sprays enveloping the gap between the pan and the boom also contain the dust such that the central suction port of the scrubber is able to draw it inside the scrubber.

• Once the dust is airborne, its capture using hydraulic sprays requires sprays producing droplet sizes in the range of the respirable dust particle size or slightly...
higher. Hence, really fine, misting or atomizing sprays need to be used subject to the constraints of available water pressures and more importantly the constraints involving very small spray orifice sizes which are likely to get plugged in a typical mine environment. Based on these constraints, appropriate sprays were selected which utilized orifice diameters the same as that of the conventionally used miner sprays, but which produced a very fine mist of water. These sprays were placed at the back corner of the pan on both sides and directed inside the pan. These sprays were introduced to allow capture of some dust (respirable and coarser than respirable) even before it actually entered the scrubber.

Despite the created shroud of sprays, some of the dust will still escape due to gaps in the shroud where the sprays do not overlap and due to the fact that at times, the cut coal traveling to the conveyor may partially obstruct the central scrubber suction port. Hence, there is a need to employ another line of defense. This line of defense is implemented in the form of flat sprays on the left side of the miner and located behind the side suction port of the scrubber. These sprays are wide-angled sprays that essentially create a seal of water from the miner to the left rib and the top to contain the dust such that it gets an opportunity to enter the side suction port. These sprays are only located on the left side of the miner as the prevailing air flow pattern in the face carries the escaping dust from the right side over the top of the miner and through the area between the left side of the miner and the rib.

To capture the dust escaping over the top of the miner, a set of five misting sprays was installed on the top of the miner directed towards the roof and angled towards the face such that the escaping dust contacts the mist and is captured. Due to the low inertia of the mist droplets, the mist migrates away from the face co-current with the air and the respirable dust increasing the residence time for the dust and mist droplets to come in contact and attach resulting in the dust-droplet aggregate to drop out.

The arrangement of sprays in the conventional and modified system is shown in Figures 1 and 2. A listing of the sprays utilized in the conventional and modified configurations is presented in Table 1.

Experimental Procedures

The modified spray system and baseline studies were conducted on the same miner operating in a belt entry development section at a Central Illinois mine. The single miner section had three 20-foot wide entries with 200-ft x 100-ft center-to-center pillars heading east and 300-ft x 125-ft staggered pillars heading south. A map of the section indicating locations of the sampled cuts is provided in Figure 3. The sampling program was conducted over three rounds of testing spanning over the time period from 6/14/05 through 8/3/05. Sampling was conducted for a total of 8 shifts as 26 cuts (11 conventional and 15 modified sprays) were sampled. The last cut of the sampling program was invalidated as a rock fall obstructed the rear misting sprays on the miner. Hence, effectively 25 valid cuts were sampled. Of these, six cuts (three each for the conventional and modified system) were cross-cuts, one was a straight initial cut and the...
The rest were cuts where the face was located 150+ feet from the Last Open Cross-cut (LOXC). Despite the differences in spray configurations, the number of sprays and volume of delivered water was maintained approximately identical in both the tested spray configurations. This was to ensure that the difference in dust capture between the two systems was not confounded by the impact of additional water. The number of sprays was maintained at 29 and 28 for the modified and conventional system while the volumetric flow rate of water was recorded to be the same at 25 gpm for both the systems.

Figure 1. (a) Conventional sprays on a continuous miner and (b) Modified spray arrangement investigated in this study.
Table 1. Conventional and Modified Spray Design.

<table>
<thead>
<tr>
<th>Location</th>
<th>No.</th>
<th>Spray No.</th>
<th>GPM @ 80 psi</th>
<th>Total GPM</th>
</tr>
</thead>
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<tr>
<td>Conventional</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Location</td>
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</tr>
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<tr>
<td>Spray No.</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPM @ 80 psi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head top/right side</td>
<td>5 3/8 BD</td>
<td>5 3/8</td>
<td>1.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Head top/center 5 3/8 BD</td>
<td>5 3/8</td>
<td>5 3/8</td>
<td>1.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Head top/left side</td>
<td>5 3/8 BD</td>
<td>5 3/8</td>
<td>1.4</td>
<td>7.0</td>
</tr>
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<td>3 3/8</td>
<td>5 1.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Head side/ right side down</td>
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<td>3 3/8</td>
<td>5 1.4</td>
<td>4.2</td>
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<tr>
<td>Throat Spray</td>
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<td>1.4</td>
</tr>
<tr>
<td>Total</td>
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| Actual delivered flow rate measured with an inline flow meter was 25 gpm for both spray configurations.

Modified Sprays Design

<table>
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<td>Spray No.</td>
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<td></td>
</tr>
<tr>
<td>GPM @ 80 psi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head top/right side</td>
<td>5 3/8 HU</td>
<td>5010</td>
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<td>7.0</td>
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<tr>
<td>Head top/center 5 3/8 HU</td>
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<tr>
<td>Head side/ left side down</td>
<td>1 3/8 HU</td>
<td>8010</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Head side/ right side down</td>
<td>1 3/8 HU</td>
<td>8010</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
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<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Pan/right side-shroud spray</td>
<td>1 3/8 HU</td>
<td>5010</td>
<td>1.4</td>
<td>1.4</td>
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<tr>
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<td>1 1/4 M18</td>
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<tr>
<td>Pan/left side-shroud spray</td>
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<td>5010</td>
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<td>1.4</td>
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<td>0.4</td>
<td></td>
<td></td>
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<tr>
<td>Second line/ left side sprays</td>
<td>2 3/8 HU</td>
<td>8010</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Throat Spray</td>
<td>1 3/8 BD</td>
<td>1 3/8</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>29</td>
</tr>
</tbody>
</table>
| This page contains proprietary information
Data Collection

The data collection in this study utilized cut-by-cut sampling. The pump locations for dust sampling shown in Figure 4 were as follows:

- 1: Intake
- 2: Near Miner Operator
- 3: Immediate Return (~ 80 ft. outby the face)
- 4: Return

The pumps were hung from the roof at all locations as shown in Figure 5.

Other measurements taken for all the cuts included the following:

- Line Curtain (LC) Air
- LOXC Air
- Car Count
- Cut Dimensions (Height, Width, Depth)
- Cut cross-section (Roof, Seam, Floor)
- Cut Time
- Water Pressure and Water Volume
Figure 4. Typical cut encountered during this study. Sampling pump locations are indicated and marked 1, 2, 3, 4.

Figure 5. Gravimetric dust sampling and instantaneous dust measurements using Personal Data Rams.

*Data Measurements and Transformations*
The filter cassettes from the dust pumps were sent to MSHA for weighing. The weight gain of the cassettes and the pump operation time were used to compute the raw dust concentrations at the four sampled locations. These dust measurements were then transformed to isolate the impacts of cut-time variability (down-time during cuts), varying LC and LOXC air flows and the differences in intake dust concentrations. The transformations were accomplished using the following methodology.

- To correct for different intake air dust concentrations, the Location 1 measurement was subtracted from the measurements for the other three locations.
- The cut-times for cuts of same dimensions may differ due to haulage delays as well as unexpected delays encountered during the cuts. These downtimes (delays) were estimated as the difference between cut time (pump run time) less average time for mining the particular cut volume. The Location 2, 3, and 4 dust concentration numbers were then adjusted for this down-time for changing the divisor time for the dust data from the actual pump run time to the expected run time. In effect, this adjustment accounts for varying production.
- Varying ventilation air flows to the face and in the LOXC directly impact the measured dust concentrations as the generated dust is either diluted by excess air or concentrated at lesser airflow. To correct for these variations, all the measured dust concentrations were normalized for 7,500 cfm of LC air and 34,000 cfm of LOXC air. The LC normalization was applied to the Location 2 and 3 samples while the LOXC normalization was applied to the Location 4 samples. It is recognized that due to recirculation of air in the face, the applied corrections for Locations 2 and 3 (particularly Location 2) are not truly indicative of the conditions near the face. Location 4 readings are however largely unaffected by recirculation at the face.

All data presented in this report is transformed cut-by-cut data and hence is not indicative of full-shift dust exposures to occupations.

**Task 1.3: Develop a computational fluid dynamics (CFD) model for a single entry in the super-section mining layout in Illinois.**

The goal of this task was to develop a CFD model of airflow in a single entry and validate the model outputs through field measurements. The project team used this CFD modeling approach to identify focus areas for controlling respirable dust in the face area. By analyzing the air flow patterns in the face area, it is possible to identify locations where recirculation areas exist and increase the exposure to dust for occupations operating in those areas. Having identified these locations, corrective actions can be planned, simulated using CFD modeling and implemented in the field after testing.
Three fundamental principles govern the physical aspects of any fluid flow: Conservation of mass, Newton’s second law, and conservation of energy. These fundamental principles can be expressed in terms of a set of partial differential equations known as the governing equations of fluid flow. CFD is the art of replacing these partial derivative equations with discretized algebraic forms which when solved gives a set of numbers for the flow field at discrete points in time and space, as the case may be, in the flow domain.

**Modeling and Validation approach**

The CFD model was progressively built using Fluent™ Software, adding complexity in steps, leading towards achieving the target of a more realistic representation of the air flows, and hence the respirable dust transport, in the face area for typical underground coal mines in Illinois. The initial model was simply an entry and a crosscut. The entry width was 20-ft and the entry height was 7-ft. The length of the entry from last open cross-cut to the face was 40 ft. The right side of the cross entry was the intake side and the left side the return. A leakage path allowing 1,000 cfm of air was set up at the end opposite the face, where pull-thru curtains are located.

After cross-validating the initial model results with findings of other researchers, a line curtain was added to the model. The line-curtain was set back 30-ft from the face and 5.5-ft from the right rib, as it would typically be located in such an entry. The results of this model were quantitatively validated against field measurements of airflows at the end of the line curtain. Subsequently, a continuous miner was added into the entry and the model results were qualitatively validated using smoke-tube visualizations of air-flow patterns and recirculations in the face area. The continuous miner was then advanced in three steps of 5-ft making sump cuts and then moved over to the left side of the entry making three additional 5-ft advances of slab cuts. A representation of the CFD model geometry is presented in Figure 6. It is proposed as a recommendation for future work that the impact of scrubber and sprays should be modeled to make the results more realistic.

**Boundary Conditions for the CFD Models**

A 3D steady state segregated implicit solver coupled with k-epsilon (2-equation) viscous model using absolute velocity formulation was used with the following boundary conditions for the CFD models.

- **Intake side**: Mass flow boundary condition-- 15.03 kg/s (at standard air density).
- **Return side**: Mass flow boundary condition-- 14.45 kg/s (at standard air density).
- **Leakage side**: Mass flow boundary condition-- 0.58 kg/s (at standard air density).
- **Roof**: Standard Wall function
- **Floor**: Standard Wall function
- **Ribs and sides**: Standard Wall function.
Figure 6. CFD model geometry of a miner in an entry at the face.

**Model Descriptions**

Twelve different models of increasing complexity to represent field conditions, changing line-curtain characteristics and advances and miner locations simulating advances in sump and slab cuts were developed. These models are described below.

*Model-1:* The basic model of a 40-ft long and 20-ft x 7-ft entry was modeled without the presence of either a line curtain or the continuous miner (CM).

*Model-2:* A line curtain was added to the Model-1 based on its typical set up in actual practice described above. The line-curtain was modeled tight against the roof and the floor.

*Model-3:* A CM was added to Model-2. The CM was set ready to make a sump cut in the right side of the entry. Machine mounted flooded bed scrubber was modeled to be in off position.

*Model-4:* This model was similar to Model-3 with some changes. The line curtain had a gap of 2-inches at the roof and floor level all along its length. Also, there was a 2-ft x 1.5-ft opening in the line curtain at the bottom located in the cross-cut. This was done to model the effect of the line-curtain lifting up from the floor due to the high cross-air velocity in the last open cross-cut.

*Model-5:* This model was similar to Model-4 with the exception that leakage at the bottom of the line-curtain along its length was closed. There was still a 2-ft x 1.5-ft
opening at the bottom in the line-curtain located in the cross-cut.

*Models-6-8:* These models were similar to Model-3 in set up except that the CM was advanced by 5-ft, 10-ft and 15-ft to simulate similar advances in a sump cut.

*Model-9:* This model was similar to Model-8 in set up except that the line curtain was advanced by 10 ft.

*Models-10-12:* These models were similar to Model-9 in set up except that the CM was moved over to the right hand side and set up to make 5-ft, 10-ft and 15-ft cuts simulating a slab cut advance.

**Model Outputs Analysis Procedure**

The outputs of the CFD models were resultant air velocities (resultant vector of x, y, and z-components of the air velocity) at any point in the domain which were plotted in vector form at discrete points in the domain for analysis and visualization of the existing air flow patterns. For further clarity, three horizontal planes, at the roof level, mid-plane level and the floor level were cut through each model and the air flow patterns in these planes were visualized separately. To estimate total air flows in cross-section of the model, a vertical plane was cut across the cross-section and the resultant velocities were extracted along this vertical plane. The resultant velocities were then aggregated across the cross-section to determine the total air flow quantities. Two additional parameters were compared for all the models. These were the reach of the line curtain air towards the face from the end of the line curtain and the size of the recirculation zone behind the line curtain. These two parameters were estimated by measuring the dimensions of these regions in the air-velocity streamlines visualization plots. Important results from the above models and their analyses are presented in the following section.

**Task 1.4:** Development of low-cost additional control devices for total and quartz dust control.

The goal of this task was to develop and demonstrate in the field low-cost additional control devices for total and quartz dust control. These devices were envisioned to be filter panels of suitable material for underground use which could be stretched across the cross-section of an entry at a suitable location away from the paths of mine equipment and also allowing for passage of personnel through an opening or a doorway within the filter panel. Two such potential locations for these filter panels are shown in Figure 7.

The desirable properties of such a filter material were identified as:

- Low-pressure drop
- High respirable dust capture efficiency
- Approved for underground use (should not be flammable and produce toxic gases upon combustion)
- Light-weight to allow easy installation and removal.
- High dust capture capacity so that replacement is necessary no more than once
every shift.

Figure 7. Possible positions of additional dust control devices.

The installation of the filter was proposed so that some of the respirable dust from upstream mining activities could be filtered before the air reached the down-stream miner and roof-bolter. This concept was discussed with two mine operators. Both mine operators were receptive to the idea and suggested developing it to assist the mines to meet regulatory requirements in the near term.

**Materials Tested**

Three suitable industrial filter materials, along with their Material Safety Data Sheets (MSDS) were supplied by a cooperating filter manufacturer for laboratory and field testing. These materials were 1-inch thick, 100% polyester, dual stage layered with the back layer having a dense needled construction. For the three different filters, the coloring of the dense backing layers was white, yellow and purple. These materials were tested in the laboratory as-received and after separating them into two layers (the colored dense layer and the white front layer. Hence, in all, nine filter materials were tested. The MSDS data for these materials were forwarded to MSHA for a review of their suitability for underground use.

**Laboratory Testing**

The development of this concept was initiated in the laboratory. A test chamber was constructed with a 15-inch x 14 5/8-inch cross-section and 6-feet in length. An exhaust fan was installed at one end of the chamber and the gaps between the chamber and the fan were sealed. Arrangements were made to introduce the filter being tested about 3-ft
(half-way) along the length of the chamber. The other end of the chamber was left open. Pre-weighed dry dust was introduced in to the test chamber at one end over a fixed length of time (20 minutes) by elutriation with a small compressed air nozzle. Air velocity measurements were taken at nine locations in a grid pattern across the cross-section of the test chamber before and after installation of the filter and at the end of the test. These measurements provided an estimate of the pressure drop across the filter and also allowed for computation of the dust accumulation capacity of the filter.

**Field Testing**

After successful testing in the laboratory, two out of the nine filters (Intact purple filter and Single-layer Yellow filter) were selected for additional field testing based on a compromise between the dust capture efficiency and pressure drop. Testing was conducted at two mines; one in Southern Illinois and one in Central Illinois. At the Southern Illinois mine, a 20-ft x 6-ft filter panel was mounted on a wooden frame and installed across the entry cross-section in the panel return (Figure 8). Gravimetric dust sampling pumps were located upstream and downstream of the filter panel as shown in Figures 9 and 10. Air velocity measurements were conducted before filter installation and at the beginning and end of the tests. The test duration was 60 minutes. Air velocity measurements were also taken across two parallel entries before and after installation of the filter to estimate the impact of the filter on air flows. These tests were repeated for both the types of filter materials.

![Figure 8. Filter panel installation and dust and air velocity measurements during field testing of the air filtration concept at a Southern Illinois mine.](image)

At the Central Illinois mine, the application of the filter panel was tested in the hack belt area where the mine was facing problems related to excessive dust, which was not a
hazard to the occupations in terms of breathing, but was still an issue with respect to visibility and dust settling downstream from that location. In this application also, the entire airflow was coursed across the filter panel. Tests were conducted with the filter panel operating dry and also with water sprays on the filter panel. Dust concentrations, air flow rate and pressure measurements were recorded upstream and downstream of the filter panel.

Figure 9. 'Total Air Filtration' concept field testing at a Southern Illinois mine.

Figure 10. Dust sampling layout of air filtration concept field testing at a Southern Illinois mine.

Task 1.5: Provide technical support to coal mines to improve dust control to meet MSHA standards.
Over the course of the project performance, the project team entertained requests from mines and referrals from MSHA to provide assistance to three mines in Illinois with respect to dust control issues at the face and elsewhere underground. The project team conducted investigation of the problem, conducted laboratory tests to develop solutions and proposed a list of recommendations for implementation at the mines. Such technical support was provided to three mines. There were additional requests for technical support which could not be fulfilled due to budgetary constraints which provided for this activity at only two mines.

**Task 2: Developing an Education Program for Reducing Out-of-Seam Dilution**

**Task 2.1: Detailed study of OSD at one mine.**

This task entailed upon a detailed study of OSD at a Central Illinois. The choice of the mine was based both on recovery ratio as well as the willingness of the mine management to initiate changes to reduce OSD. Figure 11 shows the recovery ratio of the studied mine vis-à-vis other Illinois mines. A higher recovery implies lower dilution in the mined coal.

![Graph showing OSD distribution in Illinois mines](image)

**Figure 11. OSD distribution in Illinois mines.**

To estimate reductions in dilution, a one month sampling program was initiated which was divided into two 15-day phases viz. Phase 1 and Phase 2. Phase 1 established a baseline of dilution and productivity data. An OSD educational program was developed by the project team and delivered to the continuous miner operators, roof-bolter operators and shuttle car operators after completion of Phase 1 by the mine management. Phase 2 of the sampling program followed immediately after the educational program to identify
the impact of the education program on reducing OSD.

Both Phase 1 and Phase 2 sampling programs measured roof, floor, and coal seam heights in addition to time studies. Time studies of the miner-haulage system were also performed for 3 cut-types and a total of 30-cuts, to ascertain if reduced OSD was responsible for any loss/gain in productivity.

Figure 12 shows the sampling points in an 11 entry panel over 4 pillars of advance. The entries have been numbered from 000 to 8 as shown below. The points were so selected such that the effect of both the continuous miner and scoop could be ascertained. The undarkened circles represent sampling points on the pillar ribs while the darkened circles represent sampling points in the center of the entry. The data collected from the undarkened circles namely, roof, floor and coal seam heights were used to estimate OSD due to continuous miner while the data collected at the darkened ones (mining height) were used to estimate total dilution both due to scoop and continuous miner operation. In addition to above, lengths and height of major roof falls were also measured.

Figure 12. Sampling program for the detailed OSD study at the Central Illinois mine.

Task 2.2: Develop simple low-cost concepts to minimize OSD in collaboration with Joy Mining Machinery.

Based on studies conducted in Task 2.1, the current practice at the Central Illinois mine with the dilution originating primarily from the floor was identified. Hence, it was proposed that to effectively control dilution, the mining of the floor needs to be reduced. The problem with reducing floor dilution is that the transition of the cutter head from the coal seam to the floor is not perceptible as the floor is much softer. Hence, it was apparent that other mechanical control means that restrict the reach of the cutter head into the floor need to be developed to control this dilution.
The developed concept is explained below (Figure 13).

Figure 13. A simple dilution control concept.

Let,

- $BC (h)$ = height to be cut,
- $\alpha$ = total angle which the miner drum has to move to cut height $h$.

If the two donut shaped figures near the top and bottom of DE represent the miner cutter head with radius $R$, then the real height which the miner ranging arm has to move to cut height $h$ will be given by

$$h' = h - 2R \quad (1)$$

Let $r$ be the ranging arm length and $\gamma$ be the angle to move the ranging arm by $h'$. Since the triangle ABC is isosceles ($AB = AC$; equal ranging arm lengths), both angles ABC and ACB are equal. Let both the angles be denoted by $\beta$.

Using sine rule,

$$\frac{\sin \alpha}{h} = \frac{\sin \beta}{r} \quad (2)$$

Now,

$$\beta = \frac{\pi}{2} - \frac{\alpha}{2} \quad (3)$$

Replacing (3) in (2) and solving we get,

$$\frac{r}{h} \sin \alpha = \cos \frac{\alpha}{2} \quad (4)$$

Since, $\sin \alpha = 2 \sin \frac{\alpha}{2} \cos \frac{\alpha}{2}$, \hfill (5)

This page contains proprietary information
Replacing $\cos \alpha / 2$ from (5) in (4), we get,

$$\sin \alpha / 2 = h / 2r \quad (6)$$

Thus,

$$\alpha = 2 \sin^{-1} (h/2r) \quad (7)$$

Since the miner has to range an angle of $\gamma$ for cutting $h'$,

$$\gamma = 2 \sin^{-1} (h'/2r), \text{ or,} \quad (8)$$

$$\gamma = 2 \sin^{-1} (h - 2R)/2r \quad (9)$$

The above equation shows that the angle to move by the ranging arm to cut a distance $h$ is only a function of the distance $h$ (since $r$ and $R$ are constant for a continuous miner). Thus an inclinometer measuring the angle of movement of the ranging arm can be mounted at any convenient location and connected to the miner control system to provide an indication that the set mining height (or angle of movement) has been achieved.

RESULTS AND DISCUSSION

Task 1: Dust Control

Task 1.1: Spatial evaluation of sources of total and quartz dust in a super-section and bulk analysis of coal and associated strata for quartz.

Dust data was collected around the continuous miner at different heights and distances away from the face as the entry was being mined.

Additional spatial dust distribution data was collected around the roof-bolter. The results indicated that roof-bolter did not contribute significant amount of dust in the face area. This however does not imply that the dust exposure to the roof-bolter operator is insignificant. The location and working conditions of this occupation in fact may make this occupation very vulnerable to exposure to the high quartz content dust from drilling into the roof. Further studies are required to confirm this.

Wettability tests were conducted on the roof, floor and coal strata collected from four mines in Illinois. The results are summarized in Table 2. The dust generated from the
floor is completely water-wettable. The dust generated from mining the roof strata is also almost water-wettable. The dust generated from mining the coal strata however requires the use of surfactants to achieve complete wetting within a short period of time. Within the coal seam itself, wettabilities improve in the dust from layers of coal adjacent to the floor and to a lesser extent, adjacent to the roof. There is a significant difference in surfactant concentrations required to wet the coal dust samples from different mines within Illinois.

Table 2. Wettability of coal seam and adjoining strata at a sampling of Illinois coal mines. Surfactant used was Brady’s B/F101 P for all the samples.

<table>
<thead>
<tr>
<th>No.</th>
<th>Mine</th>
<th>Unit</th>
<th>Sample</th>
<th>Complete Wettability Concentration (%)</th>
<th>Quartz (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>So. IL Mine 1</td>
<td>1</td>
<td>Coal</td>
<td>0.008</td>
<td>6.7</td>
</tr>
<tr>
<td>2</td>
<td>So. IL Mine 1</td>
<td>1</td>
<td>Floor</td>
<td>0.000</td>
<td>27.9</td>
</tr>
<tr>
<td>3</td>
<td>So. IL Mine 1</td>
<td>2</td>
<td>Roof</td>
<td>0.001</td>
<td>19.3</td>
</tr>
<tr>
<td>4</td>
<td>So. IL Mine 1</td>
<td>2</td>
<td>Coal</td>
<td>0.006</td>
<td>7.9</td>
</tr>
<tr>
<td>5</td>
<td>So. IL Mine 1</td>
<td>2</td>
<td>Floor</td>
<td>0.000</td>
<td>26.3</td>
</tr>
<tr>
<td>6</td>
<td>So. IL Mine 2</td>
<td>3</td>
<td>Roof</td>
<td>0.000</td>
<td>13.6</td>
</tr>
<tr>
<td>7</td>
<td>So. IL Mine 2</td>
<td>3</td>
<td>Top 3&quot;</td>
<td>0.010</td>
<td>6.1</td>
</tr>
<tr>
<td>8</td>
<td>So. IL Mine 2</td>
<td>3</td>
<td>Coal</td>
<td>0.003</td>
<td>1.1</td>
</tr>
<tr>
<td>9</td>
<td>So. IL Mine 2</td>
<td>3</td>
<td>Blue Band</td>
<td>0.001</td>
<td>15.5</td>
</tr>
<tr>
<td>10</td>
<td>So. IL Mine 2</td>
<td>3</td>
<td>Bottom 3&quot;</td>
<td>0.000</td>
<td>13.0</td>
</tr>
<tr>
<td>11</td>
<td>So. IL Mine 2</td>
<td>3</td>
<td>Bottom</td>
<td>0.000</td>
<td>16.2</td>
</tr>
<tr>
<td>12</td>
<td>Cen. IL Mine</td>
<td>1</td>
<td>Roof</td>
<td>0.001</td>
<td>14.1</td>
</tr>
<tr>
<td>13</td>
<td>Cen. IL Mine</td>
<td>1</td>
<td>Top 3&quot;</td>
<td>0.002</td>
<td>11.1</td>
</tr>
<tr>
<td>14</td>
<td>Cen. IL Mine</td>
<td>1</td>
<td>Coal</td>
<td>0.006</td>
<td>5.9</td>
</tr>
<tr>
<td>15</td>
<td>Cen. IL Mine</td>
<td>1</td>
<td>Bottom 3&quot;</td>
<td>0.003</td>
<td>13.4</td>
</tr>
<tr>
<td>16</td>
<td>Cen. IL Mine</td>
<td>1</td>
<td>Floor</td>
<td>0.000</td>
<td>17.2</td>
</tr>
<tr>
<td>17</td>
<td>SE IL Mine</td>
<td>-</td>
<td>Top</td>
<td>0.000</td>
<td>18.4</td>
</tr>
<tr>
<td>18</td>
<td>SE IL Mine</td>
<td>-</td>
<td>Coal</td>
<td>0.006</td>
<td>8.2</td>
</tr>
<tr>
<td>19</td>
<td>SE IL Mine</td>
<td>-</td>
<td>Floor</td>
<td>0.000</td>
<td>19.1</td>
</tr>
</tbody>
</table>

The collected channel dust samples were also analyzed by MSHA for quartz content. The results are included in Table 2 and the relationship between quartz content and wettability is indicated in Figure 14. The data indicates that the quartz content in the coal seam is significantly lower than that in the adjoining roof and floor strata. The quartz content in the floor appears to be slightly higher than that in the roof. The high levels of quartz in the roof and floor strata makes the dust makes more water-wettable. This behavior is expected since quartz is hydrophilic unlike coal which is hydrophobic.
Figure 14. Relationship between Quartz content and wettability of dust generated from coal seam and adjoining strata.

Task 1.2: Develop and demonstrate concepts for modified sprays on a continuous miner.

Based on conceptual evaluation of dust generation and propagation in the face area, a modified spray system discussed in the previous section was developed and demonstrated in the field. The field testing results indicated that the modified spray design significantly improved dust control in the face area.

To minimize the impact of variability in mining conditions on the measured dust concentrations, appropriate corrections for intake dust concentration, air flows, production, and haulage and unexpected delays were used. The nuisance variables which were not corrected by mathematical transformations included varying mining height and cut roof height, types of cuts and different testing periods. However, appropriate statistical analyses were performed to isolate the confounding effects of these nuisance variables. This was accomplished by comparing the mining height and cut roof height encountered during testing of the two spray systems which revealed that on an average, these two variables were almost identical (Table 3). Since a positive correlation (at 99.5% confidence) level was observed between respirable dust and mining height (Table 4), this factor was included as a covariate in the Analysis of Covariance (ANCOVA) procedure. To isolate the uncontrolled effect of testing over three discontinuous time periods, the data was blocked in three groups for statistical analyses. This blocking also eliminated the impact of cut-types as in one of the time periods, only X-cuts were encountered while in the other two time periods only deep cuts were made.
Table 3. Average Mining Conditions (Cut Roof and Mining Height) during the testing program.

<table>
<thead>
<tr>
<th>Sprays</th>
<th>Cut Sampled</th>
<th>Mining Height (inches)</th>
<th>Cut Rock (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>11</td>
<td>96.96</td>
<td>23.45</td>
</tr>
<tr>
<td>Modified</td>
<td>14</td>
<td>96.93</td>
<td>24.35</td>
</tr>
</tbody>
</table>

Table 4. Effect of Mining Height and Cut Rock Height on Respirable Dust Concentrations in the face area.  Reported results are Partial Correlations controlling for Testing Round, Spray System and Sampling Location.

<table>
<thead>
<tr>
<th>Mined Height</th>
<th>Correlation</th>
<th>Mined Height</th>
<th>Cut Roof</th>
<th>Dust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance</td>
<td>1</td>
<td>0.816</td>
<td>0.330</td>
<td></td>
</tr>
<tr>
<td>df</td>
<td>0</td>
<td>69</td>
<td>69</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cut Roof</th>
<th>Correlation</th>
<th>Mined Height</th>
<th>Cut Roof</th>
<th>Dust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance</td>
<td>0.816</td>
<td>0.000</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>df</td>
<td>69</td>
<td>0</td>
<td>69</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dust</th>
<th>Correlation</th>
<th>Mined Height</th>
<th>Cut Roof</th>
<th>Dust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance</td>
<td>0.330</td>
<td>0.332</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>df</td>
<td>69</td>
<td>69</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

The ANCOVA procedure revealed that the "Spray System" variable was significant at 99.6% level (Table 5). This implies that the two tested spray systems (conventional and modified) were significantly different. Further evaluation of the data comparing the average dust levels and the standard deviations for different locations and over different blocks for the two spray systems supported the finding that the modified spray system performed significantly better in controlling respirable dust at all three sampled locations, viz. near miner operator, immediate return and return (Figure 15). The reductions ranged from 4% to 80%. Most typical dust reductions were in the 40-50% range (Table 6).

Since only a limited amount of data was collected, the variances in measurements were high as is typical for field testing in underground mining conditions. However, the variances encountered in Round II of testing were low, indicating more controlled conditions encountered during this phase of testing. The low variances allowed statistical comparisons to be made for this period of testing. A "t-test" comparing the means of dust concentrations revealed that for the miner operator and immediate return sampling locations, the modified spray system provided better dust control at a statistically significant 99.7 and 99.0% confidence levels, respectively. It could also be concluded with 90% confidence that the improvements were at least 33.6% and 26.9%, respectively (Table 7).
Table 5. ANCOVA for testing the significance of treatments (one of which is the spray system used). Dependent Variable: Respirable Dust Concentration.

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected Model</td>
<td>1054.495*</td>
<td>6</td>
<td>175.749</td>
<td>20.199</td>
<td>0.000</td>
</tr>
<tr>
<td>Intercept</td>
<td>2.441</td>
<td>1</td>
<td>2.441</td>
<td>0.281</td>
<td>0.598</td>
</tr>
<tr>
<td>Testing Phase</td>
<td>87.294</td>
<td>2</td>
<td>43.647</td>
<td>5.016</td>
<td>0.009</td>
</tr>
<tr>
<td><strong>Spray System</strong></td>
<td><strong>75.508</strong></td>
<td>1</td>
<td><strong>75.508</strong></td>
<td><strong>8.678</strong></td>
<td><strong>0.004</strong></td>
</tr>
<tr>
<td>Pump Location</td>
<td>685.587</td>
<td>2</td>
<td>342.793</td>
<td>39.398</td>
<td>0.000</td>
</tr>
<tr>
<td>Mining Height</td>
<td>31.501</td>
<td>1</td>
<td>31.501</td>
<td>3.620</td>
<td>0.061</td>
</tr>
<tr>
<td>Error</td>
<td>582.957</td>
<td>67</td>
<td>8.701</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3297.666</td>
<td>74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>1637.452</td>
<td>73</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R Squared = .644 (Adjusted R Squared = .612)

Table 6. Summary respirable dust concentration measurements (in mg/m$^3$) for conventional and modified spray systems sampling. Presented data is transformed cut-by-cut data and is not indicative of a full-shift sample.

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>SD</td>
</tr>
<tr>
<td>Round I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miner Operator</td>
<td>6.467</td>
<td>2.786</td>
</tr>
<tr>
<td>Immediate Return</td>
<td>10.504</td>
<td>4.23</td>
</tr>
<tr>
<td>Return</td>
<td>0.636</td>
<td>0.515</td>
</tr>
<tr>
<td>Round II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miner Operator</td>
<td>4.348</td>
<td>0.367</td>
</tr>
<tr>
<td>Immediate Return</td>
<td>3.086</td>
<td>0.526</td>
</tr>
<tr>
<td>Return</td>
<td>1.037</td>
<td>1.116</td>
</tr>
<tr>
<td>Round III</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miner Operator</td>
<td>10.533</td>
<td>6.805</td>
</tr>
<tr>
<td>Immediate Return</td>
<td>13.311</td>
<td>3.143</td>
</tr>
<tr>
<td>Return</td>
<td>1.057</td>
<td>0.529</td>
</tr>
</tbody>
</table>

Though there was also an approximately 50% reduction in dust at the return location, this could not be established with statistical confidence. The reason was that the variance encountered during return sampling of the conventional system was high. Also, statistical comparisons for the return locations were troublesome as the LOXC air flow was very high resulting in dilution of the dust generated at the face to very low levels.
Though the data was corrected for intake dust concentrations, the return sampling location is very sensitive to intake dust concentrations in this case which may have caused the aberration in variance during the conventional spray testing in Round II.

![Graph showing dust concentration comparison between conventional and modified sprays over three rounds of testing.]

Figure 15. Results of the modified spray systems compared to the conventional spray system over three rounds of testing.

<table>
<thead>
<tr>
<th>Testing Round - Sampling Location</th>
<th>Conventional Sprays</th>
<th>Modified Sprays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round I</td>
<td>6.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Round II</td>
<td>10.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Round III</td>
<td>12.0</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Table 7. Comparison of differences between the conventional and modified spray systems during Round II of testing.

<table>
<thead>
<tr>
<th></th>
<th>H0: Conventional = Modified p-value</th>
<th>Difference (mg/m³) at 90% confidence</th>
<th>Percentage reduction at 90% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miner Operator</td>
<td>0.003</td>
<td>1.461</td>
<td>33.6%</td>
</tr>
<tr>
<td>Immediate Return</td>
<td>0.01</td>
<td>0.831</td>
<td>26.9%</td>
</tr>
<tr>
<td>Return</td>
<td>0.52</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Task 1.3: Develop a computational fluid dynamics (CFD) model for a single entry in a super-section mining layout in Illinois.

With reference to the models described in the previous section, Model-1 was created to qualitatively compare the results of similar simulations by other researchers. The simulated steady state airflow patterns were found to be in general agreement with those reported in these studies. Model-2 was then created to qualitatively observe the airflow patterns and compare them with the smoke cloud movement patterns observed in the
field. This model was also found to satisfactorily represent the field smoke-cloud movement observations. Model-3 then included positioning the CM into the entry. Steady state airflow patterns for this model with the velocity vectors indicated in m/s are shown at the mid-plane level and roof level in Figures 16 – 18. To validate the predictions of Model-3, the end of the line-curtain volumetric air flow data was collected for several cuts in the field representing the modeled cut. For an air flow of 26,000 cfm in the last open cross-cut, the model predicted the end of line-curtain air flow to be 13,000 cfm or about 50% of the last open cross-cut airflow. Corresponding measurements in the field were 10,000 cfm in the last open cross-cut and 4,700 cfm or 47% at the end of the line-curtain. Hence, the line-curtain simulation conducted in Model-3 was satisfactory. The air flow patterns for this model indicate a presence of a large area of low-velocity recirculation of the return air just behind the curtain. The ram-car operator location in this area makes that occupation most susceptible to dust exposure. The importance of the miner-operator to stay in the intake air in front of the line-curtain is also highlighted in the air-flow patterns. The location of the miner operator, even slightly away from the line-curtain intake air, puts him/her in the return-air recirculation zone and thus, increases his/her dust exposure risk. Another interesting observation across all the models is the fact that the line curtain air, with the scrubber off, fails to reach even close to the cutting face. Hence, it is clear that improving the flow of air to the face is necessary to control methane accumulations in the face area.

Figure 16. Vector plot of velocities at mid-plane level of Model-3.
Figure 17. Expanded vector plot of the central portion of Figure 16.

Figure 18. Velocity vector plot at the roof plane for Model-3.
Line curtain was set tight against the roof and floor in Model-3 which is not realistic. Furthermore, due to high resistance offered by the line-curtain to intake air flow in the last open crosscut, a portion of the curtain gets lifted up allowing another leakage path. These leakage paths were modeled in Model-4. The air flow pattern for this model at the mid plane level is shown in Figure 19. The results indicate that the size of the dead zone appearing in Model-3 is reduced significantly. This has a positive impact on reducing dust exposure of the ram-car operator. When, the floor leakage was eliminated in Model-5, the recirculation at the floor level increased as expected (Figure 20), but the recirculation at the mid-plane level (Figure 21), which is the breathing zone of the ram-car operator, remained largely unaltered compared to Model-4. Due to the leakage path at the roof level, there was also no recirculation at that level (Figure 22). The controlled leakage in the line curtain-air could be used as a potential technique to reduce ram car operator dust exposure.

In Models-6 and 7, when the CM was advanced by 5-ft and 10-ft in the process of making a sump cut, the vortex moved towards the end of the line curtain. Other than that, the air flow pattern remains almost the same as in Model-3. When the miner advanced 15-ft as in Model-8, the vortex near the end of the line curtain moved further ahead and reached the end of the line curtain (Figure 23). With the advancing miner, the miner operator had more space to stand behind the miner in fresh air reducing the probability of him/her stepping into the recirculation zone just behind the line curtain. By advancing the line curtain by 10-ft in Model-9, the vortex near the end of the line curtain moved back to just behind the end of the line curtain as expected and was not of much consequence. There was still no significant amount of air reaching the face.

![Figure 19. Vector plot of velocities in m/s at mid-plane level of Model-4.](image-url)
Figure 20. Velocity vector plot in m/s on the floor plane for Model-5.

Figure 21. Vector plot of velocities in m/s on mid-plane level of Model-5.
Figure 22. Velocity vector plot in m/s on the roof plane for Model-5.

Figure 23. Vector plot in m/s of air flow pattern for Model-8 at mid-plane level.
When the miner moves to the left-side as in Model-10, there is no vortex formation or churning of air flow in the face area. Hence, cutting in this area appears to be favorable to the ram-car operator. For Model-11 (Figure 24) and Model-12 the air flow patterns are similar to those indicated for Model-10.

Figure 24. Vector plot in m/s of air flow pattern for Model-11 at mid-plane level.

In addition to the visualization of air-flow streamlines within the model domain, comparisons were made between different models on two additional parameters. These were; (a) the area of recirculation zone behind the line curtain at the roof, mid-level and floor plane, and, (b) the reach of the line curtain air to the face from the end of the line curtain. This was primarily done to evaluate the effect of line curtain leakages (Table 8) and cut advances (Table 9) on these two parameters.

From Table 8 it can be observed that as the leakages increase, the reduced air-velocity at the end of the line curtain at the leakage plane results in a corresponding decrease in the reach of the line-curtain air towards the face in that plane. It is also observed that the reach of the line curtain air is the highest at the roof level followed by the floor level and then by the mid-plane level. This appears to be a direct result of the obstructions to air-flow posed by the continuous miner at those levels. In case of Slab cuts (Table 9) the miner position allows less open area for the air to retreat from the face which results in higher resistance and reduced air-flow. The absence of recirculation zones in slab cuts is explained by the fact that the only area that is left open is between the line curtain end and the miner from where the air forces itself out and dissipates the recirculation zone.
The recirculation zones are observed to be the maximum for Model-3 (no leakages). While leakages from the top and bottom of the line curtain help reduce the recirculation zones, only roof-level leakage further reduces the top and mid-plane recirculation. The project team has made the observation that the probable reason is that air leaking from both roof and floor levels creates a vortex at the mid-level plane leaving the recirculation zone in this area intact, even as the recirculations at the roof and floor levels are reduced. With leakage only from the top, the air gets a chance to flow with lesser resistance reducing the dead zones at the top and mid-plane level better. It is to be reemphasized here that the mid-plane level behind the line curtain is the breathing zone of the ram-car operator making recirculations in this area particularly detrimental.

Table 8. Areas of recirculation zone behind line curtain and the reach of the line curtain air to the face from the end of the line curtain in the roof, mid-level and floor planes for the CFD models evaluating leakage paths along the line curtain.

<table>
<thead>
<tr>
<th>Model Description</th>
<th>Recirculation Area (ft^2 in Plan View)</th>
<th>Line Curtain Reach (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roof Plane</td>
<td>Mid Plane</td>
</tr>
<tr>
<td>Model 3 - Tight LC against the roof and floor.</td>
<td>151.5</td>
<td>65.6</td>
</tr>
<tr>
<td>Model 4 - Roof and Floor level leakage paths along the length of the LC. Additional Leakage in LOXC area.</td>
<td>37.1</td>
<td>54.5</td>
</tr>
<tr>
<td>Model 5 - Roof level leakage along LC length and additional leakage in LOXC area.</td>
<td>0</td>
<td>14.7</td>
</tr>
</tbody>
</table>

Based on these studies, the following broad conclusions can be made.

- The recirculation behind the line-curtain increases the dust exposure of ram-car operators. The recirculation reduces as the distance between the end of the line-curtain and the miner increases. Also, the presence of leakage paths over the top of the line-curtain reduces the recirculation. Hence, the exposure of ram-car operators to respirable dust at the face area can be minimized by better curtain handling practices and through ideas such as introducing leakage paths in the center of the curtain at the ram-car operator breathing level.

- All the models indicate that the line-curtain air reaching the face is limited. This is unfavorable from methane dilution point of view but can be used to an advantage for improved dust control. Lower air quantity at the face helps in containing and concentrating the dust close to the face where no occupations are
present. Hence, effective use of hydraulic sprays and directing the face air into the scrubber may achieve effective dust suppression.

- Line-curtain leakages at the floor level eliminate recirculation only at the floor level. However, since the breathing zones for all occupations are either at the mid-plane level or near the roof level, leakages at the floor level should be minimized to increase end-of-curtain air quantity and velocity. The air can be used more effectively to ventilate the face or allow for leakage at the roof and mid-plane levels to improve dust exposures of occupations operating in the face area.

- Slab cuts appear to be less dusty for the ram-car operators due to absence of recirculations in the areas where they operate.

Table 9. Areas of recirculation zone behind line curtain and the reach of the line curtain air to the face from the end of the line curtain at the mid-level plane for the CFD models evaluating different depths of sump and slab cuts.

<table>
<thead>
<tr>
<th>Model Sump Cuts</th>
<th>Recirculation Area (ft² in Plan View)</th>
<th>LC Reach (ft)</th>
<th>Model Slab Cuts</th>
<th>Recirculation Area (ft² in Plan View)</th>
<th>LC Reach (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 3 - Initial Setting</td>
<td>66</td>
<td>7.4</td>
<td>Model 10 - 5-ft Advance</td>
<td>-</td>
<td>5.5</td>
</tr>
<tr>
<td>Model 6 - 5-ft Advance</td>
<td>212</td>
<td>15.7</td>
<td>Model 11 - 10-ft Advance</td>
<td>-</td>
<td>6.4</td>
</tr>
<tr>
<td>Model 7 - 10-ft Advance</td>
<td>172</td>
<td>17.0</td>
<td>Model 12 - 15-ft Advance</td>
<td>-</td>
<td>5.4</td>
</tr>
<tr>
<td>Model 8 - 15-ft Advance</td>
<td>164</td>
<td>18.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 9 - 15-ft Advance and LC Advance by 10-ft</td>
<td>200</td>
<td>18.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Task 1.4: Development of low-cost additional control devices for total and quartz dust control.

The studies on development of an innovative total air filtration concept were initiated with identification of suitable filter materials for potential underground use. Nine filter materials were tested in the laboratory in a set up described above. The results presented in Table 10 indicate that the dust capture efficiencies ranged from 9% to 89%. However, high capture efficiencies were associated with higher pressure drops across the filter material (Figure 25). Hence, to achieve a balance between capture efficiency and resistance to air flow, two materials (2-Layer Purple and 1-Layer yellow) were selected for additional field testing. These materials provided a dust capture efficiency of 40-60% at a moderate pressure drop of 0.0055 to 0.0078 inches of water column under laboratory conditions. During field testing, however, respirable dust reductions of 13% and 12%, which corresponded to dust reductions from 2.53 mg/m³ to 2.19 mg/m³ and 2.23 mg/m³ to 1.96 mg/m³, were achieved with these materials. The reason for lower dust capture
Table 10. Laboratory filter panel testing results.

<table>
<thead>
<tr>
<th>Filter Material</th>
<th>Air Flow* (fpm)</th>
<th>Head Loss</th>
<th>Resistance</th>
<th>Dust Concentration (mg/m³)</th>
<th>Dust Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unobstructed</td>
<td>Pre-Test</td>
<td>Post-Test</td>
<td>(in. wc)</td>
<td>Input</td>
</tr>
<tr>
<td>White - 2 Layer</td>
<td>366</td>
<td>109</td>
<td>0</td>
<td>0.00761</td>
<td>276</td>
</tr>
<tr>
<td>White - 2 Layer (Repeat)</td>
<td>385</td>
<td>111</td>
<td>0</td>
<td>0.00847</td>
<td>296</td>
</tr>
<tr>
<td>Purple - 2 Layer</td>
<td>366</td>
<td>129</td>
<td>88</td>
<td>0.00760</td>
<td>197</td>
</tr>
<tr>
<td>Purple - 2 Layer (Repeat)</td>
<td>375</td>
<td>127</td>
<td>94</td>
<td>0.00776</td>
<td>207</td>
</tr>
<tr>
<td>Yellow - 2 Layer</td>
<td>366</td>
<td>110</td>
<td>0</td>
<td>0.00731</td>
<td>260</td>
</tr>
<tr>
<td>Yellow - 2 Layer (Repeat)</td>
<td>375</td>
<td>111</td>
<td>60</td>
<td>0.00800</td>
<td>280</td>
</tr>
<tr>
<td>Purple - Back Layer</td>
<td>374</td>
<td>204</td>
<td>152</td>
<td>0.00613</td>
<td>63</td>
</tr>
<tr>
<td>Purple - Front Layer</td>
<td>374</td>
<td>249</td>
<td>209</td>
<td>0.00486</td>
<td>34</td>
</tr>
<tr>
<td>Yellow - Back Layer</td>
<td>374</td>
<td>154</td>
<td>31</td>
<td>0.00724</td>
<td>132</td>
</tr>
<tr>
<td>Yellow - Front Layer</td>
<td>374</td>
<td>229</td>
<td>157</td>
<td>0.00545</td>
<td>45</td>
</tr>
<tr>
<td>Yellow - Front Layer (Repeat)</td>
<td>375</td>
<td>229</td>
<td>184</td>
<td>0.00550</td>
<td>45</td>
</tr>
<tr>
<td>White - Back Layer</td>
<td>385</td>
<td>140</td>
<td>95</td>
<td>0.00802</td>
<td>176</td>
</tr>
<tr>
<td>White - Front Layer</td>
<td>385</td>
<td>238</td>
<td>212</td>
<td>0.00571</td>
<td>43</td>
</tr>
</tbody>
</table>

* C/S Area: 1.52 ft²

** P.U. - Practical Units
efficiency in the field was that the tests were run only for duration of 60 minutes each. As seen in Figure 25, the dust capture efficiency increases as a function of pressure drop. If the tests were carried out for a longer duration, higher capture efficiencies should have resulted, albeit at an increased pressure drop as the captured dust closed any openings or leakages across the filter.

![Figure 25. Relationship of pressure drop across filter panel with the dust capture efficiency measured during laboratory experimentation using different varieties of filter materials.](image)

During the duration of the tests, a moderate drop in air velocities was observed in the entry after introduction of the filters (Figure 26). The project team believes that these issues can be resolved effectively through proper installation of pull-thru curtains, changes in regulator openings and appropriate simulations of mine ventilation within a panel. This was however not a part of the research task this year and as such, will be attempted in subsequent studies.

To estimate filter change requirements during the shift, a dust reduction target from 2 mg/m³ to 1.5 mg/m³ was established. The filter change timing was set at the time when airflow reductions across the filter were greater than about 30%. At this level of air reduction the filter capacity was estimated at about 850 mg/ft² of respirable dust. Hence, it appears that at 20,000 cfm of air in the LOXC at 2.0 mg/m³ being filtered to a level of 1.5 mg/m³ without causing more than a 30% reduction in airflow before the filter is changed, total filter area of 160 ft² would be required. The entry cross-section is typically about 20-ft x 6.75-ft or 135 ft². Hence, it appears that the life of the filter would be slightly less than duration of the entire shift. A more appropriate filter material selection is possible that will ensure that the filter installation is effective for the duration of at least one full-shift making its use more practical.

To determine the permissibility of the filter material for underground use, the MSDS information on the filter materials was forwarded to MSHA. After preliminary
evaluation, the material did not appear to present any major issues for underground use. However, it was concluded that to obtain the final permissibility approval, laboratory studies on flammability and combustion gases analyses by MSHA would be required.

Figure 26. Airflows (in cfm) across three return entries during field testing of the innovative "Total Air Filtration" concept for (a) 1-Layer Yellow Filter and (b) 2-Layer Purple Filter at (i) before filter installation, (ii) after filter installation, and, (iii) at the end of test period. Most airflow measurements indicated are direct measurements. The measurements that were not taken have been simulated using a VentSim PC model.

Additional tests on the low-cost filter panel for dust control were conducted at a Central Illinois mine. These tests were conducted in the production shaft hack belt area. The
results indicated that the filter panel, when used in conjunction with water sprays, was the most effective measure for controlling the dust. Downstream dust concentrations as measured by the personal data rams were reduced from 14.5 mg/m$^3$ to 5.3 mg/m$^3$. The reductions using the existing system employed by the mine using just water sprays only reduced the dust concentrations marginally. When the filter panel was installed initially, air reduction and pressure drops were only marginal. However, the air flow reduced significantly after 15 minutes. Given these results, it appears that the application of the filter panel in the face area may be effective. The filter panel blinding may not be as big an issue when used in the last open crosscut where the dust concentrations are an order of magnitude lower than in the area where these tests were conducted. Additional testing will however be required to establish the developed concept beyond any doubt.

Task 1.5: Provide technical support to coal mines to improve dust control to meet MSHA standards.

During the project performance period, the project team provided technical support related to dust control to three mines in Illinois. At a Central Illinois mine, the project team's recommendations in dealing with dust control in their materials handling shaft were implemented which led to a 50% reduction in dust.

At the request of the mine, the project team visited Pattiki mine which included a one day visit underground to review their dust control issues. MSHA representatives also spent the day underground with the project team. Wettability studies on the ROM coal were completed before the mine visit. At this mine, dust samples indicated that the miner operator is exposed to too much dust and the mine is non-compliant with MSHA requirements. Prior to leaving the mine, a four step improvement process was proposed for the mine: 1. Modifications of the continuous miner spray systems, 2. Modifications of scrubber inlets, and spray systems, 3. Coursing the ventilation air to the face area and to the operator as mining progresses, and 4. Education program for miner operators. The mine professionals and MSHA professionals from Vincennes office are in contact with the mine and are monitoring their progress.

The project team visited Wabash mine to discuss dust control problems at their mine. Mr. Charles Weilbaker of MSHA had coordinated this meeting after discussions with the mine health and safety staff. About 8 persons attended the meeting including SIU staff and Mr. Charles Weilbaker of MSHA. After two hours of discussions of problem areas and possible solutions, the following action items were agreed upon and given to the mine staff for implementation.

- Install a flow meter on the continuous miner and monitor water volume.
- Change spatial locations of sprays around the loading pan.
- Reduce spray water pressure from 120-130 psi to about 90 psi.
- Advance the curtain regularly and keep the miner operator just behind the curtain.
- Monitor respirable dust using mini-rams and dust pumps for blow-through cuts toward the intake.
- Increase the water pressure in the scrubber to about 40 psi.
There were additional requests for technical support from other mines which could not be entertained due to budgetary constraints which had only allowed for this activity at two mines.

**Task 2: Developing an Education Program for Reducing Out-of-Seam Dilution**

**Task 2.1: Detailed study of OSD at one mine.**

The first phase of the OSD study was to establish a benchmark of current practice. Miner-Haulage time-study data was collected in addition to the data on existing dilution levels at the mine. A total of about 30-cuts of time-study data and 700 points of dilution data were collected over a 10 pillar advance and across all entries.

The measurements of mining height, coal seam height, and, roof and floor dilutions for the pre-education period indicated that the average mining height at mine during that period was 6’ 6 3/8”. With a coal seam height of 5’ 7 3/8”, the out-of-seam dilution height was close to 11-inches. Of this, less than 1.5-inch was roof dilution. Hence, the out-of-seam dilution at this mine primarily consisted of floor dilution. The mine required a minimum working height of 6-foot. Thus, there was an opportunity to reduce dilution by almost 6’ 6 3/8”. This amount of reduction in dilution can have a large impact on profitability as has been shown by the authors in earlier studies. Hence, a goal to reduce dilution by about 3-inches was established as a first step with the expectation that as the face crew gets comfortable working in these altered conditions, further reductions in dilution may be attempted. Interestingly, the collected data indicated that the desired mining height (with 3-inch reduction in dilution) was inadvertently being achieved during Phase 1 for about 8-12% of the time as indicated in Figure 27. This further supported the feasibility of consciously reducing dilution to achieve the established goals.

Based on the data collected in Phase I sampling studies, an OSD education program was prepared by the project. This program was delivered by the mine management to the miner operators and roof-bolter operators working in the section being sampled. The education program was immediately followed by Phase II sampling program which replicated the Phase I studies to determine the impact of the education program on achieving reduced dilution.

As part of post-education Phase 2 sampling program, another 2-weeks of data collection was accomplished. Face haulage time studies and dilution measurements were conducted as in Phase I. Results of the face haulage time studies indicated a marginal increase in loading times during Phase II data collection period (38 seconds/car in Phase II as compared to 37 seconds/car in Phase I). This difference was however not statistically significant at 0.05 level of significance. Correspondingly, the effect on productivity was also not significant. The difference itself could be explained as a result of the cautious approach of the continuous miner operators in cutting coal as attempts were being made to reduce dilution.
Figure 27. Entry measurements, (a) Mining Height, (b) Coal Seam, (c) Roof Dilution, and, (d) Floor dilution measured during benchmarking (Phase I) OSD studies at the Central Illinois mine.

Figure 28 shows the progression of mining heights and dilution from pre-education program period through 2 weeks of post-education period sampling. Center of coal seam is represented by y-coordinate of 0 ft. Red Green and Blue colors represent the thicknesses of mined roof, coal and floor. The figure indicates that there was a post-education reduction in roof dilution. The floor dilution however was reduced immediately after the education program but drifted back to pre-education levels over next several days.

The near absence of roof dilution and a large amount of floor dilution both the Phase I and II sampling programs also indicated that the miner operators can control dilution effectively if the interface between coal and the adjoining strata is apparent as in the case of the coal-roof interface. However for the coal-floor interface, the transition is not apparent resulting in excessive mining of the floor. Hence, it appears imperative that a mechanism is required that can provide feedback to the miner-operator as the coal-floor interface is reached or when the desired mining height is reached.

Figure 29 shows the OSD for different seam heights observed in the mine. As expected and as observed in the pre-education sampling, OSD is seen to increase with decreasing
seam height. The relationship between OSD height and seam height is indicated as:

Figure 28. Progression of mining heights and dilution from pre-education program period through 2 weeks of post-education period sampling.

Figure 29. Relationship of OSD with seam height.
The total Mining Height is the sum of the OSD height and the seam height. Hence,

\[ OSD_{Ht} = -0.8331 \times Seam_{Ht} + 5.4945. \quad (10) \]

Substituting (10) in (11), we have,

\[ Mining_{Ht} = OSD_{Ht} + Seam_{Ht}. \quad (11) \]

Hence, the change in mining height as a function of the change in seam height can be represented as,

\[ \frac{d(Mining_{Ht})}{d(Seam_{Ht})} = 0.1669. \quad (13) \]

Hence, for every 1-inch reduction in seam height, mining height only decreases by about 0.17-inches. From pre- to post-study, coal seam height decreased by 1.92 inches which should have resulted in a decrease in mining height of only 0.32 inches. However, the mining height decreased by almost 1-inch. This excess decrease in mining height is thus attributed to the education program. When only the period immediately after the education program is considered, instead of the reduced seam height resulting in mining height reduction of 0.32 inches, the actual reduction was almost 1.7 inches. This indicates that the education program was indeed effective, at least to some degree, in controlling dilution.

The summary results of Phase I and Phase II dilution measurements are provided in Table 11 as key findings are summarized below.

- A decrease of 1-inch is indicated in the mining height. However, since the coal seam height decreased due to geologic conditions, dilution actually may have increased compared to the pre-training period.
- Dilution would have been higher if mining height would not have decreased. Hence, education program does appear to have had an impact.
- Immediately after the education program, mining height reduction was ~1.5-inch. However, towards the end of the sampling program, mining height drifted back to the pre-education program levels. This emphasizes a continued need for monitoring and retraining the operators.
- As conscious efforts were made to reduce dilution, reduction in roof dilution was achieved at some level of significance. This is despite the fact that the roof dilution was already low.
- Considering that the entire post-education study occurred in an area with poor roof conditions compared to the pre-education program which occurred entirely in good roof conditions, the above finding is even more significant.
• It appears that efforts to control floor dilution were ineffective. Floor dilution in the post-education period actually appears to have increased. The different roof conditions in the pre and post study periods may have had a bearing on the increased floor dilution.
• The inability to effectively control floor dilution is attributed largely to the fact that it is very difficult for the miner operator to detect the transition of the cutting head from coal to the floor. This emphasizes the importance of developing interface detection and simplistic automated mining height control technologies.

Table 11. Dilution measurements summary.

<table>
<thead>
<tr>
<th></th>
<th>Floor (ft)</th>
<th>Roof (ft)</th>
<th>Coal (ft)</th>
<th>Mining Height (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Educ Avg.</td>
<td>0.80</td>
<td>0.09</td>
<td>5.64</td>
<td>6.49</td>
</tr>
<tr>
<td>Post-Educ Avg.</td>
<td>0.87</td>
<td>0.06</td>
<td>5.48</td>
<td>6.41</td>
</tr>
<tr>
<td>Pillar 1</td>
<td>0.78</td>
<td>0.08</td>
<td>5.48</td>
<td>6.35</td>
</tr>
<tr>
<td>Pillar 2</td>
<td>0.80</td>
<td>0.07</td>
<td>5.51</td>
<td>6.37</td>
</tr>
<tr>
<td>Pillar 3</td>
<td>0.95</td>
<td>0.04</td>
<td>5.51</td>
<td>6.46</td>
</tr>
<tr>
<td>Pillar 4</td>
<td>1.00</td>
<td>0.07</td>
<td>5.40</td>
<td>6.47</td>
</tr>
</tbody>
</table>

Task 2.2: Develop simple low-cost concepts to minimize OSD in collaboration with Joy Mining Machinery.

The OSD studies in Task 2.1 clearly indicated that to successfully control dilution, in addition to education and training, it is necessary to have a system which will enable the operator to detect the transitions out of the coal seam, particularly, from the coal seam to the floor. There are elaborate technologies available to achieve this. Their widespread application has however been limited in part due to high cost and technical problems. Hence, the project team in this task conceptualized a very simple technology that will allow the miner operator to mine only a desired height and thus reduce OSD. This concept relies on the fact that at most mines, the transition between the coal seam and the roof is obvious. If the current mining height is 6.53-feet as indicated in Figure 30, it requires movement of the ranging arm of about 38° from the roof level. Hence, if the targeted mining height were only 6-feet, the ranging arm would only have to move by about 35°. This control can be accomplished with an inclinometer mounted on the ranging arm. As soon as the cutter head hits the roof, the miner operator can reset the inclinometer. After that, once the inclinometer measures angular displacement of say, 35°, it will send a signal to the operator which will alert the operator that the targeted mining height of 6-ft has been reached and he/she should not mine into the floor anymore.
CONCLUSIONS AND RECOMMENDATIONS

This research focused on improved dust control and reduced OSD at underground Illinois coal mines. The dust control research focused on spatial evaluation of dust around the continuous miner, development and demonstration of modified spray systems, development and validation of a CFD model for a single entry and development and demonstration of a low-cost dust control technology. The project team also provided technical consultation to three Illinois coal mines for improving dust control at their specific mines through specific recommendations for implementation.

The OSD research involved development of an education program directed towards the continuous miner operator and roof-bolter operators to increase their awareness of OSD. Detailed sampling studies were conducted before and after the education program to quantify the success of the education program. Based on the sampling data, a new technology was conceptualized to assist the miner operator in controlling mining height.

Specific findings of these studies and recommendations for future work are presented below.

Conclusions

- Spatial evaluation of dust around the continuous miner revealed higher respirable dust concentrations near the roof level and closer to the face. This information is helpful in focusing future dust control efforts in this area.
- Dust sampling around the roof-bolter indicated that it did not significantly contribute to the respirable dust at the face.

This page contains proprietary information
• Channel sampling of the coal seam and adjoining strata indicated that dust generated from the roof and floor materials is water-wettable. On the other hand, dust generated from the coal seam requires the use of surfactants to achieve complete wetting within a short period of time. The requirement of surfactant to achieve this complete wetting can vary significantly from one coal to another.
• The modified spray system demonstrated in the field achieved 40-60% dust reductions compared to the conventional spray system. These results were statistically significant at high confidence levels.
• The CFD modeling of aerodynamic conditions in the face area provided invaluable insights into analyzing the problem of occupational dust exposures. Though the modeling needs to be refined further, it is clear that improvements in line-curtain management practices are necessary to reduce dust exposures to the occupations operating in the face area and to dilute methane concentrations in the face area.
• The low-cost dust control technology "Total Air Filtration", tested in the field achieved reductions in respirable dust. The reductions were however associated with moderate increases in pressure drops. The project team however believes that this can be overcome through proper installation of pull-thru curtains, changes in regulator openings and appropriate simulations of mine ventilation within a panel.
• The technical consultation and recommendations for dust control for specific requirements of three Illinois coal mines were largely successful. At one particular mine, reductions in dust in the material handling shaft by as much as 50% was reported.
• The OSD education program was successful in reducing OSD at the sampled mine by approximately 1-inch. The reductions were about 1.5-inches immediately following the education program. The OSD drifted back to pre-education levels as reinforcement of the achieved improvements were not conducted. This indicated that it is important to monitor and educate the face crew on an ongoing basis till maintaining reduced OSD becomes a habit.
• Through the OSD sampling program, it became apparent that a feedback device is necessary for the miner operator to be able to control OSD by staying out of the floor. Such a technology has been conceptualized and has received favorable reviews from mine operators.

Recommendations

• A more detailed evaluation of spatial distribution of dust sources in the entire super-section should be conducted. This should involve collection of full-shift instantaneous data recording the timing of mining activities being performed at specific times. Dust sampling is also required to determine the exposure of roofbolter operators directly from the dust generated during drilling into the roof. In addition, dust sampling is necessary around the feeder and along the ram car travel paths to determine the dust exposure to ram-car operators during dumping and travel. These activities will assist in the development of a holistic approach to dust control in underground coal mines.
• SIU professionals believe the performance of the modified spray system can be further improved by varying water volume and water pressure for sprays associated with different hypotheses which led to the development of the modified system. The performance should also improve with improved ventilation conditions at the face. These changes need to be incorporated and further field testing is required to document the additional improvements from these changes.

• Prior to implementing improvements to line-curtain management, CFD modeling conducted here needs to be extended to include scrubber operation and the presence of directional fan sprays on the miner. These enhancements to the model will significantly change the aerodynamics in the face area. In addition, CFD modeling effort should be extended to simulate steady state air flow patterns near the face area for various stages of advance of the machine while making sump cuts and slab cuts. These simulations will shed better light on the air flow and respirable dust transport patterns near the face area.

• Validation of CFD model results by field observations in this project has been encouraging. However, since the mining process is dynamic in nature, dynamic CFD modeling of the face area is perhaps the best approach to better identify the best way to control respirable dust in the face area. As dynamic modeling is very complex, time consuming and requires huge processing power, stage-wise steady state simulations can be used as an alternative to approximate a truly dynamic simulation. This steady state model representing the different stages during the cutting process should provide better insight for improved dust control near the face area.

• To make the 'Total Air Filtration' technology a commercial success, efforts need to be directed towards simulation of mine ventilation and incorporating changes which will allow overcoming the increased pressure drop introduced by the filter.

• The filter material needs to be tweaked to give it a life-span matched to at-least one shift-duration to make its use practical.

• The filter material needs to be approved by MSHA for underground use.

• The success of the OSD education program needs to be re-measured with presence of monitoring, feedback and retraining of the face crew by mine management.

• The conceptualized OSD control technology needs to be developed further and tested in the field to demonstrate its success.

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