ABSTRACT

Over the past 3-years, SIU researchers have developed a host of technologies to reduce the dust exposure of underground coal miners in Illinois. In this project, the primary goal was to demonstrate these technologies in the field and further improve the understanding of dust generation and propagation in the face area. Specific tasks in this project included: 1) demonstration of SIUC proven concepts of modified wet scrubber and modified sprays on a continuous miner for improved dust control, 2) spatial dust inventory of a super-section and bulk analysis of coal and associated strata for quartz, 3) extending the developed CFD model of a single entry to include the effects of scrubber on airflow in the face area and development of a methodology to model multiphase physics, and, 4) demonstrating a low-cost dust control filter for use in mines.

The spatial dust inventory studies indicated the necessity of improving dust control at the feeder in the face area. The collected data indicated that more than 33% of the ram-car operator occupational dust exposure occurs near the feeder and almost 60% exposure occurs away from the face. Analysis of the coal seam and adjoining strata for quartz content and wettability at two mines indicated high quartz contents in the roof and floor strata along with lower wettabilities for the coal. Demonstration studies of the comprehensive dust control package on continuous miners achieved tremendous success. A 62% and 38% lower dust exposure was documented for the miner operator and the ram-car operator near the face area. The results generated significant interest and enthusiasm at the mine where this demonstration was conducted. Significant strides were also made towards commercialization of the dust filter concept. Demonstration of a suitable filter material successfully reduced dust concentrations by 37% and 51% when used in a dry and wet mode. This compares very favorably with earlier efforts at dust reduction by the mine which only reduced dust by 18%.

CFD modeling studies incorporating scrubber indicated that the scrubber increases airflow in the face area. The scrubber also alters the airflow patterns in the face area to positively (reduce) impact of dust on the miner and ram car operator occupations. Increase in airflow at the roof level due to the scrubber indicates that the ignition probability would be reduced. It was also found that scrubber capacities in excess of the line curtain airflow may in fact be detrimental to dust control.
EXECUTIVE SUMMARY

Dust control can be a major deterrent to increasing production and lowering production costs. The push for increased production and reduced cost has several mines operating at or over the allowable MSHA limit for respirable dust. In the recent past, several coal mines in Illinois have experienced MSHA citations and/or work stoppages due to non-compliance with dust standards. Therefore, optimizing existing dust control systems and finding new ones has become a top priority. Towards that end, researchers at SIU have developed several promising technologies to achieve improved dust control. These developments range from improvements in the diagnostic wettability test, improvements in the design of the flooded-bed scrubber to improve its efficiency, improvements in the locations of scrubber inlets, development of a ‘total air filtration’ device and a completely redesigned spray system on the continuous miner. Computational Fluid Dynamics (CFD) studies of the miner operating in the face area have yielded insights into the propagation of dust which were otherwise not possible. Several of these technologies have already been implemented by the industry. Hence, in this project, an integrated dust-control package incorporating the best aspects of all these technologies developed over the years was planned for demonstration at one Illinois coal mine. More specifically, four activities were proposed in this project.

1. Perform spatial evaluation of sources of total and quartz dust in a super-section and bulk analysis of coal and associated strata for quartz at two mines. Such data had already been collected at several other mines in Illinois in previous studies. This data was to be collected for development of spatial dust control strategies using the “systems approach to dust control” developed by the project team.

2. Incorporate SIU developed modified wet scrubber, modified spray systems, and dust wettability concepts into a single continuous miner. Demonstrate field performance of the modified continuous miner to control dust in the face area.

3. Further extend previous CFD studies for a single entry to include the effects of scrubber and water sprays which have a profound impact on air flow patterns in the face area. The goal was also to develop an algorithm for implementing multiphase water-dust-air interaction incorporating dust suppression.

4. Demonstrate a low-cost dust control filter for protecting down-stream occupations from the continuous miner and for dust-control in other areas such as production shaft (specific to the demonstration site mine) and belt transfer points.

The accomplishments achieved in this project in each of this area are summarized below.

Spatial Dust Sampling and Dust Inventory in a Super-section

Coal and adjoining roof and floor strata samples were collected at two additional Illinois coal mines. Such samples were collected and analyzed at four other coal mines in the previous project. The collected samples were evaluated for wettability and analyzed for quartz content. The results reconfirmed findings of the earlier study that the source of quartz was primarily the roof, floor and the immediate adjoining sections of the coal seam. The quartz contents in the roof and floor were in the 18-22% range with the coal
seam quartz content was in the range of 5-8%. This finding further supports the authors’ contention that out-of-seam dilution must be reduced to the maximum extent possible to improve Illinois coal mining productivity and reduce costs. There are a host of other compelling reasons for reducing out-of-seam dilution which have been put forth by the authors in earlier studies. Studies on wettability indicated that the roof and floor materials are largely water-wettable with varying degrees of coal wettability at different Illinois mines.

In order to collect data towards development of a “systems approach” to dust control, four shifts of sampling were conducted at one mine in Southern Illinois to determine the sources of dust generation and dust propagation in the entire section. Strategically located dust pumps and anemometers in the section were used to capture the required information. These studies resulted in a very interesting finding. It was found that up to 60% of the haulage unit operator dust exposure occurred away from the face, a large proportion of which was at the feeder location. Hence, dust control at the feeder was indicated as a high priority area for future studies geared towards reducing the dust exposure of haulage unit operators.

Air Filtration Technology

During the previous studies by the authors, a novel dry and wet air dust filter concept was conceived and demonstrated successfully at two mines. The dry air filter during field testing provided respirable dust concentration reductions from 2.53 mg/m³ to 2.19 mg/m³ and 2.23 mg/m³ to 1.96 mg/m³ for two different filter materials. The capture efficiencies could have been much higher, albeit at an increased pressure drop, if the tests would have been run for 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 believed that this issue could be easily resolved through proper installation of pull-thru curtains and changes in regulator openings.

Another issue related to the use of this filter in the previous studies was related to the flammability of the filter material. Hence, newer filter materials made of fiber glass and steel wool were sought out from several different filter manufacturers. Suitable samples of candidate materials were procured and tested in the SIU-JOY dust control laboratory. A suitable fiberglass filter material with low resistance (0.007 in. wc @ 300 cfm) and 20-30% dust reduction was identified for field demonstration. Several other non-combustible filter materials for wet use were also evaluated in the laboratory. With these materials, a range of dust capture efficiencies from 58% to 88% were achieved at different levels of pressure drops (ranging from 0.9 to 6.15 in-wc @ ~6,600 cfm) and water usage (0.9-3.3 gpm). Two of the filter materials were demonstrated at a central Illinois mine which was facing a major issue related to dust in the production shaft area. Despite the efforts of the mine staff, excessive dust was a problem in the production shaft area prior to the demonstration. The existing dust concentration in the production shaft area was 13.5 mg/m³ as measured by a real-time dust monitor (PDR). The water sprays employed by mine staff were only able to reduce the dust by 18% down to 11.1 mg/m³.
also measured by the PDR. SIU research staff conducted three sets of tests with two suitable filter types identified during laboratory testing. The two filter types were a steel wool filter and a fiberglass filter. The steel wool filter was operated with and without water sprays while the fiberglass filter was only operated in the dry mode. The dry steel wool filter provided a dust capture of 37% at a negligible pressure drop. When fine misting water sprays were used on the steel wool filter, the dust capture increased to 51% again with a negligible pressure drop. The filter screen also remained clean and no change in air flow characteristics was observed as a function of time. The dry fiberglass filter however did not perform as well achieving only 11% dust capture while introducing a significant resistance to air flow. However, the steel wool filter material is the material of choice for underground coal mine use as it is non-combustible. The mine staff was extremely impressed by the performance of the steel wool filter.

CFD Modeling

CFD modeling of the scrubber has further improved the understanding of the aerodynamic conditions in the face area which has a direct relation with the problem of occupational dust exposures in the face area. The modeling activities in 2004-2005 revealed 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. With the addition of the scrubber, the following broad conclusions were made from the modeling studies in this project.

- The scrubber allows more fresh air to be pulled down the line curtain which improves dust dilution in the face area. This is a well known phenomenon which validates the CFD finding.
- Increased airflow in the face area results in increased fresh air for the miner operator positively impacting that occupations dust exposure. The increased air flow also results in a reduced area of low air velocities behind the end of the line curtain allowing more flexibility to the miner operator to be situated for operation.
- The scrubber discharge reflects off the rib in the heading and provides increased airflow at the ram car operator location. Again, the low air velocity “dead zone” in this area is reduced realizing a lower dust exposure to the ram car operator occupation. However, for this to be realized in practice, the ribs must be wet to prevent duct entrainment. The authors had made this recommendation in previous studies based on physical observation. CFD modeling supports this recommendation.
- The presence of scrubber aids increasing the reach of the line curtain air. When the line curtain air can reach further up, particularly near the roof level, reduced ignition probabilities will result.

CFD modeling studies have also provided indications towards finding appropriate scrubber capacity. The results indicate that intake air at the end of the line curtain must be matched with the scrubber capacity. The air quantity at the end of line curtain must be at least equal to the scrubber capacity. It would be preferable to have this value to be slightly larger than the scrubber capacity. Where it is less than the scrubber capacity, recirculation of air in the face area can negatively impact dust exposure of the miner.
operator and haulage unit operator. The end of the line curtain air tries to short circuit directly into the scrubber inlet across the miner without sweeping the face. During the slab cutting operation, the end of the line curtain air will short circuit into the scrubber suction inlet on the right hand side of the miner and reduce the efficiency of scrubber suction inlet on the left hand side of the miner. This will negatively impact the dust exposure of the haulage unit operator.

**Demonstration of an Integrated Dust Control Approach on a Continuous Miner**

In this task, a comprehensive package for dust control on a continuous miner which included previously developed modifications to the scrubber, scrubber intakes and the chassis spray system was demonstrated at a central Illinois mine. Side-by-side comparisons of the modified miner and regular miner were made. The results indicated the following.

1. Mining conditions in the areas where regular miner and modified miner were tested were relatively similar. Actually, the modified miner was cutting slightly thicker roof (4.1 inches) as compared to regular Miner (2.1 inches).
2. The miner operator on the modified miner was exposed to 62% less respirable dust as compared to regular miner.
3. The ram car operator associated with the modified miner was exposed to 38% less respirable dust as compared to regular miner.
4. The return air on the modified miner had 19% less respirable dust as compared to the regular miner.

These results support the findings of the modified spray system studies conducted earlier at different mines in Illinois on four occasions. The performance of the comprehensive package impressed the mine staff and has been discussed with other mines in the state. These studies have generated a significant interest in the industry and the PI has been approached by other mines to implement the developed dust control package.

Overall, the studies in the dust control area conducted as part of this project were very successful. The comprehensive dust control package for the continuous miner provided outstanding dust reductions for the face occupations. A filter with the desired permissibility characteristics was successfully demonstrated and was able to achieve a significantly enhanced dust capture compared to earlier efforts of the mine to control dust. Investigative studies of dust inventory revealed that efforts are required to control dust at the feeder to reduce the exposure of ram-car operators. Furthermore, CFD modeling provided valuable insights and directions towards determination of the optimum scrubber capacity. All these studies together have improved the state-of-the-art in underground room-and-pillar coal mining dust control. The outcomes of this study promise to achieve lower occupational dust exposures to the miners in the face area, enhance productivity and lower production costs for Illinois mines as a result of better dust control.

*Pages 6 and 8-11 of this document contain proprietary information*
OBJECTIVES

The goal of this proposed research was to develop and demonstrate advanced mining technologies related to dust control that would allow mine operators to enhance productivity and reduce production costs in the near term. Towards achieving this goal, investigative and demonstration activities were planned and accomplished. The investigative tasks included a spatial dust inventory in the super-section to identify the sources of dust generation and exposure and a computational fluid dynamics model to better understand dust propagation and exposure in the face area. The demonstration tasks involved demonstration of a continuous miner with comprehensive modifications which were developed and evaluated by the authors over the past four years. Another task also involved the demonstration of a wet and dry filter system which was also developed by the authors in the past as part of Illinois Clean Coal Institute (ICCI) funded research. A brief description of each task is provided below.

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

The goal of this task was to systematically collect and analyze spatial respirable dust data around the sources of dust generation and distribution in a super-section. In previous studies by the authors efforts were focused on investigating the dust generation and propagation in the face area. In this project, the scope of the study was extended to cover the entire super-section to include the impact of dust generation at the feeder.

Task 1.2: Field demonstration of integrated dust control concepts in and around the face area

Over the last four (4) years, SIUC researchers have developed three (3) major concepts for dust control in the face area: 1) Systems approach to dust control, 2) Modified wet scrubber, and 3) Modified sprays on continuous miner. The first has been implemented in Illinois mines through technical support. The modified scrubber concepts were tested as part of an earlier project at an Illinois mine in Year 2005 with good results. The modified spray system was also developed by the authors and tested at two locations in Illinois with great success in the Years 2005-2006. This task aimed to package all the developments in improved continuous miner dust control together and demonstrate it at a mine alongside a conventional system.

Task 1.3: Continue to develop a computational fluid dynamics (CFD) model for a single entry

A CFD model represents a numerical model of airflow in an entry. CFD modeling of ventilation problems is relatively new (Sullivan and Van Heerden, 1993; Moloney et. al., 1999; Wala et. al., 2003) and has not been harnessed for development of dust mitigation technologies based on the findings. Numerical modeling of airflow in and around the face can be a powerful tool for a better understanding of spatial distribution of dust and methane and developing strategies to effectively reduce their concentration in mine
environment. In a previous ICCI funded project completed by the authors, significant strides were made in analyzing air-flow patterns (and hence the dust) in the face area at different stages of advancing the cut. In this project, this task extended the previous studies by incorporating the scrubber which has a profound impact on the air–flow in the face area, to obtain a more realistic representation. Path-paving work on incorporating multi-phase water-dust-air interaction and dust capture was also attempted. Even though a complete implementation of this interaction could not be accomplished in the time-frame of the software license, an algorithm for achieving the same was developed.

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

The project team developed low-cost devices for total and quartz dust control in 2004-2005. These control devices consisted of a low-pressure drop industrial filter to capture some of the respirable dust before it reaches the downstream miner, bolters, and haulage units in a single-split super-section. These devices were tested in a mine by locating them in the panel return entry. Here, these filter devices reduced dust concentration in the return air stream from 2.45 mg/m³ to 1.58 mg/m³ with only a moderate drop in air velocity. More importantly, the total air quantity in the last open crosscut remained unchanged. The tested filters were however combustible in nature. Hence, in this project, two different types of filter materials were identified which possessed the desired characteristics which included non-combustibility. These filters were demonstrated with and without water sprays in the production shaft area of an Illinois mine.

INTRODUCTION AND BACKGROUND

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 believes 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. In addition, SIU
researchers have been involved in the development of low-cost air filtration systems to protect sensitive occupations at the face from excessive dust exposures. A summary of SIU’s research in these dust control areas over the past 5 years is presented below.

- During 2001-2002 studies, surfactants were used to increase the effectiveness of a continuous miner scrubber for total and quartz dust control. Statistical design of experiments was used to evaluate effects of different variables. The effectiveness of four commercially available surfactants was tested on the Illinois No. 5 seam coal. An empirical model of dust concentration in the mine atmosphere as a function of three important scrubber parameters was established. The variables were number of layers, spray water pressure, and the surfactant concentration. The number of layers in the scrubber filter was found to be the most significant parameter having an impact on the dust concentration followed by spray pressure and surfactant concentration which were also statistically significant.

- During 2002-2003, the wet scrubber was modified. A wettability test was developed that assesses surfactant effectiveness better than the sink test (Chugh et. al. 2004). Mine water was typically found to increase surfactant requirements by 75-100% compared to that using tap water. A two-filter concept was developed and optimized for surfactant spray volume and surfactant concentration variables. Surfactant concentration was found to have a significant effect on dust concentration. The optimum dust concentration in the range 1.6-1.8 mg/m³ was achieved for two mines using spray volumes of 2 gpm for Spray 1 (intake side) and 3 gpm for Spray 2 (return side), 5 layer scrubber filters, operating spray pressure of 40 psi and a surfactant concentration of 0.007%.

- In 2003-2004, a new scrubber unit was installed, modified, and demonstrated in the field at Viper mine. Additional changes to miner spray configurations and relocation of scrubber inlets were also implemented. Field studies of this modified miner validated the concepts developed by the project team and achieved reduced dust concentration and improved visibility in the face area. The modified miner, showed total and quartz dust reductions in the face return air, and for the miner and ram car operators. Continued independent testing by the mine and regulatory agencies verified these findings.

- In 2004-2006, a modified spray system on a continuous miner was developed and tested at two mines in Illinois with great success. Spatial distribution of dust in super-section face areas was developed for two mines. Bulk sampling of coal, immediate roof and floor strata was also performed to analyze the sources of quartz. A CFD analytical model of air flow in the face area was also developed which provided new insights into the problem of dust control at the face. Low-cost auxiliary dust control devices such as filter panels in entries were also evaluated in field testing.

In the present project, efforts were directed towards gaining a better understanding of the dust exposure sources in the super-section and demonstration of the developed dust control technologies as a complete package. More specifically, the investigative studies involved spatial dust inventory in the super-section to identify the occupational dust exposure of ram-car operators and the development of a CFD model of the face which
incorporated realistic representations involving scrubber and water-sprays while laying the foundation of a multi-phase, multi-component dust capture model. The demonstration studies involved demonstration of a modified continuous miner with modified scrubber, modified scrubber inlets and a modified spray system as part of an enhanced comprehensive dust control package. The auxiliary filter system was also demonstrated using different non-combustible and hence permissible materials operating in wet and dry configurations.

EXPERIMENTAL PROCEDURES AND MODEL DEVELOPMENT

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 in the super-section. Previous studies in this area focused on detailed sampling around the continuous miner. In this project, the entire section was sampled with a particular emphasis on dust generation near the feeder. Figure 1 presents the generalized sampling map indicating the typical section layout and indicating locations where air flow and gravimetric dust sampling was conducted. Samples were collected for four (4) shifts yielding four (4) sets of data points. The airflow measurements indicated the leakage paths of air and the propagation of belt entry and travelway air through the section. The average of the dust concentrations recorded at the indicated locations over four (4) sampling shifts provided the necessary data for completing the dust inventory in the face area when combined with the face dust sampling data and the ram-car time study data.

In addition to the spatial dust inventory, channel samples were collected from two Illinois mines. The collected channel samples included separate samples of the coal and the adjoining roof and floor strata. Within the coal seam itself, the top and bottom 3-inches of the seam were separately sampled. A representative split was obtained from the collected samples and it was ground in a laboratory ball mill. The ground material was then dry-screened at 500 mesh in a Roto-Tap sieve shaker. The -500 mesh fraction was then subjected to wettability tests according to the procedure described in Chugh et. al. 2004, and using Brady’s B/F101 P surfactant. Samples of this material were also analyzed for quartz content by MSHA laboratories.

Task 1.2: Field demonstration of integrated dust control concepts in and around the face area

As described above, SIU project team has been pursuing research in the area of dust control over the past five years. Three significant developments achieved during this time period with respect to modifying the dust control system on the continuous miner were tested together in this task. The tested developments include the (i) modified scrubber system, (ii) modified scrubber inlets, and (iii) modified spray system. Details of these developments have been reported in earlier research reports and publications by the
authors (Chugh et. al., 2005a, 2005b, 2006a) and are summarized here.

Figure 1. Spatial dust inventory in a super-section.
Figure 2. Sprays and screen in the unmodified scrubber.

Figure 3. Modified two-filter, two-spray system.
Table 2. Cut types sampled in the baseline and modified miner dust sampling. Initial and Short cuts are cuts into entries where the face is less than 40-ft from the last open cross-cut. Deep cuts are cuts where the distance is greater than 40-ft. Cross-cuts include the left and right turns and blow-throughs.

<table>
<thead>
<tr>
<th>Cut Type</th>
<th>Number of Cuts Baseline Miner Sampling</th>
<th>Number of Cuts Modified Miner Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial/Short</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Deep</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Cross-cuts</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>18</td>
<td>13</td>
</tr>
</tbody>
</table>

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.

Data Collection

The data collection in this study utilized the cut-by-cut sampling procedure which was developed by the authors and utilized in earlier studies (Chugh et. al., 2006b). The pump locations for dust sampling shown in Figure 8 were as follows:

- 1: Intake
- 2: Near Miner Operator
- 3: Near Ram Car Operator (at the time of car loading)
- 4: Return

The pumps were hung from the roof at all locations as shown in Figure 9.

Other measurements taken for all the cuts included the following:

- Line Curtain (LC) Air
- Last Open Cross-cut (LOXC) Air
- Car Count
- Cut Dimensions (Height, Width, Depth)
- Cut cross-section (Roof, Seam, Floor)
- Cut Time

(a) (b)
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 8,000 cfm of LC air and 18,000 cfm of LOXC air. The LC normalization was applied to the Location 2 samples while the LOXC normalization was applied to the Location 4 samples. Depending on the type of cut, LC or LOXC normalization was applied to Location 3. For shorter cuts where the ram car operator will mostly be in the LOXC, the LOXC normalization was used. For the deeper cuts where the ram car operator will be into the entry, he will only receive the LC air returning from the face. Hence, the LC normalization was applied in this case. 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 Continue to develop a computational fluid dynamics (CFD) model for a single entry**

This task extended previous work by the authors by incorporating a miner equipped with a scrubber to analyze its impact on air flow patterns in the face area. In addition, an algorithm was developed to incorporate dust capture physics into the CFD model.

**CFD**

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 Approach**

The CFD model was progressively built using Fluent™ Software. 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. 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
scrubber intakes and exhaust were located at their usual locations on the miner. A representation of the CFD model geometry is presented in Figure 10. The scrubber was

![Figure 10. CFD model geometry of a miner in an entry at the face.](image)

**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).
Scrubber Exhaust—7,500 cfm (also run at 5,625 and 9,375 cfm)
Roof: Standard Wall function
Floor: Standard Wall function
Ribs and sides: Standard Wall function.

**Model Descriptions**

Four models were computed using CFD. These models were; (i) baseline model, without the scrubber, (ii) Model with scrubber operating at its rated capacity of 7,500 cfm, (iii) with the scrubber operating at 75% of its rated capacity, and, (iv) with the scrubber operating at 125% of its rated capacity.

**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.

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

The goal of this task was to demonstrate in the field, low-cost dust 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 would allow for passage of personnel through an opening or a doorway within the filter panel. 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. Other applications of this filter material would be downstream of the development work cutting overcasts and underpasses to keep the generated dust out of the intakes of mining sections.

**Laboratory Testing**

Initial tests in the laboratory and the field in earlier studies had yielded encouraging results. The filter materials tested in those studies however did not meet MSHA permissibility criteria for non-combustibility. Hence, in this task suitable material characteristics desirable for this application were identified as listed below.

- Low-pressure drop
- High respirable dust (less than 10 micron) 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 capacity so that replacement is necessary no more than once every shift.

Four materials expected to achieve these requirements were selected and tested in the laboratory. Three of these materials were made of fiber-glass and one was a stainless steel-wool filter. Both materials were incombustible meeting the primary requirement for underground use. The fiberglass filters were tested in a test chamber which was 15-inch x 14 5/8-inch in 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 into 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 pressure drop across the filter and also allowed for computation of the dust accumulation capacity of the filter. The steel-wool filter was tested in a set-up sketched in Figure 11. Pressure and velocity measurements were taken at the indicated sampling locations marked 1-6. Sampling points 1-2-3-4 were located upstream of the filter and spaced horizontally across the duct. Sampling points 5-6 were downstream of the filter in the center of the duct and spaced approximately 16-inches apart.

![Figure 11. Schematic of the laboratory test set-up utilized for evaluation of the steel-wool filter.](image)

**Field Demonstration**

From the laboratory tests, one fiberglass material and a 1/8-inch thick steel-wool material were found to satisfactorily meet the requirements outlined above. These two materials which were suitable for different applications were identified for field demonstrations. The fiberglass material was chosen for dry application at the face where portability would be necessary. For applications at fixed point locations the more robust steel-wool filter was selected.
These materials were demonstrated in the field over long durations (3-5 hour tests) to determine their dust capture efficiency and resistances to air flow. The steel wool filter was operated with and without water sprays to accomplish higher dust capture efficiency and filter cleaning with the use of water. A set of 6 misting sprays delivering 0.4 gpm of water at 80 psi were placed 4–ft away from the filter panel spraying vertically down such that a uniform spray coverage was achieved on the filter panel. Tests were conducted in the production shaft area of a central Illinois mine since the mine was facing major dust issues in this area. Figure 12 shows the field demonstration test setup at the mine. It can be seen that prior to this demonstration, the mine was already using sprays for dust control which were not very effective. During the demonstration tests, these sprays were turned off. The steel-wool filter was operated with and without water sprays installed by SIU. The fiberglass filter was only tested dry. Dust concentrations upstream and downstream of the filters were monitored. Air flow measurements through the filter were also recorded over periodic intervals.

Figure 12. Filter demonstration at a central Illinois mine.

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

Wettability of Coal and Adjoining Strata
Wettability tests were conducted on the roof, floor and coal strata collected from four mines in Illinois. The results are summarized in Table 3. The dust generated from the floor is completely water-wettable. The dust generated from mining the roof strata is also mostly 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. Even though there is not a significant difference in surfactant concentrations required to wet the coal dust samples from different mines within Illinois, previous studies by the authors looking at other different mines indicates that this difference can be significant.

The collected channel dust samples were also analyzed by MSHA for quartz content. The results are shown in Table 3. 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. All these results are in very good agreement with previous studies by the authors at other mines.

*Dust Inventory in a Super-section*

To identify the sources of dust exposure to ram-car operators, dust and air flow sampling was conducted at various locations in the super-section as described earlier. Four shifts of samples were collected and the analyzed dust concentrations are presented in Table 4. An example of the surveyed data is presented in Figure 13. It is very interesting to observe that the dust concentration at the feeder over an average of four samples is as high as 2.376 mg/m³. Since a significant portion of the ram car operator time is spent at this location either dumping coal or waiting at the change-out, a significant portion of that occupation’s dust exposure occurs here. This is a new finding of this study which has previously been overlooked. In the past, efforts to reduce ram car operator dust exposures focused only on the face area. These results clearly indicate that dust control measures at the feeder are essential and will go a long way in reducing the occupational dust exposure of ram car operators.

<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>Cen. IL Mine</td>
<td>W</td>
<td>Top 3&quot;</td>
<td>0.002</td>
<td>10.6</td>
</tr>
</tbody>
</table>
To quantify the proportion of dust exposure received by the ram car operators at different locations during the shift, computations were conducted based on the collected data. A production rate of 2,200 raw tons per unit shift using four 10-ton ram cars was assumed. Hence, each ram car carried 55 loads during the shift. Time study data was used to determine average time spent by the ram-car operator at each location during the course of a shift. The results presented in Table 5 indicate that excluding the intake air dust exposure, the ram car operator receives approximately 33% of the exposure near the feeder and 39% at the face. The rest of the exposure is during the travel back and forth between the face and feeder. A portion of the dust encountered by the ram-car operator is again due to the propagation of the dust generated at the feeder towards the return due to airflow in that direction. Hence, it is clear from this analysis that dust control at the feeder is as important as dust control at the face to reduce ram-car operator dust exposure.
Figure 13. Dust inventory around a super-section.
Table 4. Dust inventory in a super-section.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Dust Concentration (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intake</td>
</tr>
<tr>
<td>Test 1</td>
<td>0.550</td>
</tr>
<tr>
<td>Test 2</td>
<td>0.253</td>
</tr>
<tr>
<td>Test 3</td>
<td>0.005</td>
</tr>
</tbody>
</table>
Table 5. Ram car dust exposure accounting.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time / car load (seconds)</th>
<th>Time (minutes)</th>
<th>Dust* (mg/m³)</th>
<th>Exposure (mg.hr/m³)</th>
<th>Percent Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake</td>
<td>-</td>
<td>480</td>
<td>0.268</td>
<td>2.144</td>
<td>23.3</td>
</tr>
<tr>
<td>Loading</td>
<td>58</td>
<td>53.17</td>
<td>1.592**</td>
<td>1.411</td>
<td>15.3</td>
</tr>
<tr>
<td>Face Change-out</td>
<td>62</td>
<td>56.83</td>
<td>1.401*</td>
<td>1.327</td>
<td>14.4</td>
</tr>
<tr>
<td>Dumping</td>
<td>33</td>
<td>30.25</td>
<td>2.108</td>
<td>1.063</td>
<td>11.5</td>
</tr>
<tr>
<td>Feeder Change-out</td>
<td>40</td>
<td>36.67</td>
<td>2.108</td>
<td>1.288</td>
<td>14.0</td>
</tr>
<tr>
<td>Travel</td>
<td>-</td>
<td>303.08</td>
<td>0.393</td>
<td>1.985</td>
<td>21.5</td>
</tr>
</tbody>
</table>

* Dust concentrations are net of intake dust concentrations.  
** Loading dust exposure is an average value obtained extensive prior sampling.  
+ Dust exposure at face change-out is an average of the return and interior (ram car travel paths) since ram car waiting at change-out at the face is typically either in the return air or one cross cut away from the face.

Task 1.2: Field demonstration of integrated dust control concepts in and around the face area

This task involved testing of the modified scrubber, modified scrubber intakes and a modified spray system which were successfully developed and demonstrated individually in earlier projects by the authors. In this project, the modified miner incorporating all these changes was compared with the baseline miner in terms of dust control. The results of these tests are summarized in Table 6. The mining conditions during the modified miner and baseline testing were very similar as shown in Table 7. The presented results indicate the following.

1. Mining conditions in the areas where regular miner and modified miner were tested were relatively similar. Actually, the modified miner was cutting slightly thicker roof (4.1 inches) as compared to regular Miner (2.1 inches).
2. The miner operator on the modified miner was exposed to 62% less respirable dust as compared to regular miner.
3. The ram car operator associated with the modified miner was exposed to 38% less respirable dust as compared to regular miner.
4. The return air on the modified miner had 19% less respirable dust as compared to the regular miner.

The mine staff, witnessing the tests, and the face operators were extremely impressed with the modified miner performance.

The limited number of tests that were allowed by the mine limited the ability of the project team to obtain variances that were low enough to facilitate robust statistical analysis of the data. However, 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 97% and 93.0% confidence levels, respectively. It could also be concluded with 90% confidence that these improvements were at least 16.2% and 4.9%, respectively (Table 8). Though there was also an approximately 19% reduction in dust at the return location, this could not be established with statistical confidence due to the high variance in measurements.

Even though the number of tests conducted as part of this testing program was limited, there have been four earlier rounds of testing which have indicated equally good results. The summarized dust control performance achieved over this and the other four rounds of testing is presented in Figure 14. Consistent and large reductions in dust have been demonstrated and documented repeatedly. Hence, the authors are very confident that the developed dust control package demonstrated here is a success and has a lot of potential for Illinois mines.

Table 6. Summary respirable dust concentration measurements (in mg/m³) 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>Miner Operator</td>
<td>1.000</td>
<td>0.959</td>
</tr>
<tr>
<td>RC Operator</td>
<td>0.798</td>
<td>0.477</td>
</tr>
<tr>
<td>Return</td>
<td>1.664</td>
<td>1.105</td>
</tr>
</tbody>
</table>

Table 7. 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>Mined Roof (inches)</th>
<th>Mined Floor (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>18</td>
<td>79.7</td>
<td>2.1</td>
<td>10.5</td>
</tr>
<tr>
<td>Modified</td>
<td>13</td>
<td>77.1</td>
<td>4.1</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Table 8. Statistical comparison of differences between the conventional and modified spray systems.

<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>0.029</td>
<td>0.162</td>
<td>16.2%</td>
</tr>
<tr>
<td>Immediate Return</td>
<td>0.064</td>
<td>0.036</td>
<td>4.5%</td>
</tr>
</tbody>
</table>
Returns

|       | 0.449 | -   | -   |

Figure 14. Summary of dust reductions achieved by the modified sprays and modified scrubber over the regular miner. Round IV results refer to the results obtained and reported as part of this project and include modifications to the scrubber in addition to the spray modifications. Rounds I-IV were at a central Illinois mine while Round V was conducted at a southern Illinois mine.

Task 1.3 Continue to develop a computational fluid dynamics (CFD) model for a single entry

In the previous year project with ICCI, the authors had simulated airflows around the face area of a single entry with curtains installed as in physical practice. During this year studies, scrubber was incorporated into the model to assess its impacts on airflows in the face area and dust exposure of different occupations in the area. Furthermore, the effect of scrubber capacity on airflows in the face area was evaluated. The baseline model included 7,500 cfm scrubber capacity. The effect of reducing and increasing this capacity
by 25% was modeled in relationship to the quantity of air reaching end of the line curtain.

Results of the CFD simulations are presented in Figures 15-22. Figure 15 shows the airflow patterns along the mid-plane for the baseline model which did not include the scrubber. This model was used to compare with the results of scrubber addition. This model output was also compared with the baseline models from previous studies and was found to be in very good agreement.

Figure 16 shows airflows along the mid-plane of the entry with scrubber operating. With the addition of scrubber, it is clear that the line curtain airflow increases since the pressure drop between the end of the line curtain and last open crosscut increases. The air also travels farther beyond the line curtain so that the miner operator is better protected from high dust concentration in the face area. This suggests that the miner operator should not be permitted to go beyond 1-2 feet beyond the line curtain unless the scrubber is operating.

The major effect of scrubber operation appears to be on dead zones around the haulage unit operator. The air velocities near the ram car operator increase as the dead zone of air in the baseline model is disturbed by the scrubber discharge reflecting off the rib in the heading. This is a desirable outcome, if the ribs are wet and the scrubber discharge does not entrain dry dust from the ribs. This finding supports the authors’ recommendations in earlier studies that the coal ribs need to be wetted to improve ram car operator dust exposure. This finding also supports the authors’ recommendation to the mine operators that if the scrubber discharge blows straight into the entry, it may improve the ram car operator dust exposure.

In an attempt to find an answer to the question of optimum scrubber capacity in relation to the quantity of air reaching the end of the line curtain, models runs were made at different scrubber capacities. As discussed above, the scrubber operating at the conventional rating of 7,500 cfm offers several benefits. In addition to the qualitative discussion of results for 75% and 125% scrubber capacity model runs that follows, quantitative measurements of the line curtain air volume were obtained to aid the discussion. It was determined that the line curtain air volumes for the 7,500, 5,625 and 9,375 cfm scrubber capacity cases were 7,738, 7,074 and 7,435 cfm, respectively. These values were computed by averaging the air velocity across the cross-section. This compares with the line curtain airflow of 5,543 cfm without the scrubber. This quantitative data indicates that increasing the scrubber capacity beyond a certain level does not result in increased line curtain airflow. This is likely to be a result of the line curtain path resistance itself. When the scrubber output is reduced to 75% (5,625 cfm) similar improvements in the dust control aerodynamics are observed as in the 7,500 cfm case (Figure 17). The effects are however less pronounced. The dead zones around the haulage unit operator increase in size as compared to the 7,500 cfm case. The higher scrubber capacity case however presents some intriguing results (Figure 18). As mentioned above, since the line curtain air flow is not increased, short-circuiting of the line curtain air to the scrubber may occur. This actually worsens the dust situation in the face area as is evidenced by the re-emergence of low velocity recirculation patterns (dead
The aerodynamics at the roof level are very important from ignitions perspective since it is at this level that sparks are created and the relative concentration of fine dust is the highest. Hence, model results at this roof-plane were analyzed in particular. Higher airflow at the roof level will dilute dust and methane and hence reduce ignition probability. The model outputs at the roof level indicate that in the baseline (no scrubber) case, air velocities of about 1.0 m/s extend close to the face (Figure 19). In comparison, for the 7,500 cfm case (Figure 20), the air velocities at the roof plane are lower at about 0.50-0.75 m/s. However, the distribution of velocities is uniform across the face. This is likely a result of the suction of the left scrubber inlet which forces the line curtain air to spread-out across the width of the entry. Since, the air is spread-out more uniform; the velocities are slightly lower compared to the case without any scrubber. For the 75% scrubber case (Figure 21), the velocities at the roof level near the face are very small (<0.25 m/s). This is expected as the both the line curtain air volume as well as the suction imparted by the scrubber are lower. This is clearly not a desirable situation. Figure 22 presents the results for the 125% scrubber capacity case. It is seen that the air reaching the face is lower than that with the scrubber operating at 7,500 cfm. This is most likely a result of increased short-circuiting of the line curtain air as the scrubber is starved for air as it is rated at higher capacity than the air reaching the end of the line curtain. This situation is also clearly undesirable. Overall, the results indicate that higher scrubber capacities are desirable only if the line curtain can bring in air to the face which is in excess of the scrubber capacity.

**Multiphase Physics**

To date, all attempts at CFD analyses in underground room-and-pillar and longwall mines have utilized air flow as an indicator of dust flow. This assumption is valid, particularly of the respirable dust fraction which has a very small settling velocity and can be expected to just follow the direction of the entraining air. These studies have provided a valuable insight into the dust propagation and dust concentrations in and around the operating areas. However, dust suppression using hydraulic sprays is utilized universally and is very effective. Hence, to model the dust distributions and flow at the face, it is essential to develop multiphase physics within the CFD model to incorporate the interactions between water, air and dust particles. In this project, a pioneering attempt to model this multiphase physics was undertaken. An algorithm to accomplish the same was developed but was not incorporated in the model due to limitation of
Figure 15. Baseline model (without scrubber) – airflows in the mid-plane.

Figure 16. 7500 cfm scrubber model – airflows in the mid-plane.
Figure 17. 5,625 cfm scrubber model – airflows in the mid-plane.

Figure 18. 9,375 cfm scrubber model – airflows in the mid-plane.
Figure 19. Baseline model (without scrubber) – airflows near the roof-plane.

Figure 20. 7500 cfm scrubber model – airflows near the roof-plane.
resources. The concept of the algorithm was based on monitoring dust particle and water droplet size distributions and numbers in individual mesh cells in the CFD model and allowing their interaction based on probability functions to determine the likelihood of dust particle-water droplet attachment. The attached particles were assumed to gain enough mass to drop out, while the remainder of the water droplets and dust particles were carried forward into the adjoining mesh cells based on their velocity vectors. A step-by-step algorithm for modeling this multiphase interaction physics is represented in Figure 23 and discussed below.
Figure 23. Schematic representation of dust-air-water interaction physics indicating mechanisms of dust capture and transport through the model.

{ 
For all cells query cell size --> $d_c$
}

for every size dust particle in cell (Range : 0-5, 5-10, 10-25, 25-75, 75+ microns)
{ 
  count number of dust particles in size range --> $n_d$;
  query the diameter --> $d_d$; (or calculate $d_d$ from geometric mean of diameters)
  count number of water particles in size range --> $n_w$; ($n_w$ will be an array)
  query their diameter -->$d_w$; ($d_w$ will be an array -- or determine $d_w$ using geometric means of diameters)
}
Now query each particle density and classify it as dust and water (water=1000 kg/m$^3$, dust !=1000 kg/m$^3$).

Calculate particle-droplet size ratio, r, as,
if $d_w > d_d$, $r = d_w/d_d$,
else $r = d_d/d_w$;

For every dust particle in a size range, calculate interactions with water droplets of all sizes as,

Calculate droplet-particle collision and attachment probabilities ($p_c$ and $p_a$):

$$p_c = \frac{n_d \cdot n_w \cdot (d_d^3 + d_w^3)}{d_c^3}/f;$$
(Collision probability is the ratio of the volumes occupied by the dust particles and water droplets within the volume of the mesh cell. The value ‘f’ is the fraction of particles being tracked in the model)

$$p_a = \frac{1}{1+8.19 \cdot \exp(-3.98 \cdot r))} - 1.05/r;$$
(The probability of attachment upon collision is a function of the relative sizes of the dust particles and water droplets. The attachment probability is higher if their sizes are comparable and lower if one is much larger than the other. The probability of attachment ($p_a$) as a function of the ratio of particle-droplet diameters is presented in Figure 24. The attachment function is fitted to representative data.)

Calculate dust capture as,

$$C_p = \text{Sum over } d_w (k \cdot n_d \cdot p_a \cdot p_c)$$
(Dust capture requires collision to occur and an attachment after the collision. The number of dust particles interacting in such way is $n_d$. ‘k’ is a fitting parameter)

Calculate remaining dust:

if $C_p > n_d$, $n_d = 0$
else $n_d = n_d - C_p$
(If number of particles that can be captured is more than the number of particles present, the remaining particles are zero. Else, the remaining particles are the initial number of particles, less the particles captured)

Calculate total remaining dust:

Sum all the remaining dust in each size fraction.
An example computation following this algorithm is presented in a spreadsheet format in Figure 25. Example dust capture calculations are shown for dust particles of 40, 20 and 10 micron sizes. It can be seen that dust-water interactions with higher ‘r’ are associated with higher probability of attachment.

\[ p_a = \frac{1}{1+8.19 \exp(-3.98*r))} - \frac{1.05}{r} \]

**Figure 24.** Dust particle-water droplet attachment probability function.

### Cell Size
- \( dc = 1000 \) microns

### Fraction of particles/droplets tracked
- \( f = 0.1 \)

### Fitting Parameter
- \( k = 5 \)

### Size Distribution Data (Specified by Rosin-Rammler Distribution)

<table>
<thead>
<tr>
<th>Dust Particle (microns)</th>
<th>Number</th>
<th>Water Droplet (microns)</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>80</td>
<td>2</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>60</td>
<td>3</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>50</td>
<td>5</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>40</td>
<td>7</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>
Task 1.4 Commercial development of low-cost additional devices for total and quartz dust control.

Laboratory Tests

The selection of suitable filter materials for field demonstration first involved a series of laboratory tests. The fiberglass filter materials were tested only in a dry mode while the stainless steel-wool filter was tested both in a dry and wet mode. Tests on three fiberglass materials involved measurement of reduction in airflow and the dust capture efficiency of the filters. Table 9 lists the results obtained from the three tested materials.
The three materials provided similar performance and hence, Material 2, which provided the highest dust capture was selected for field demonstration. The laboratory test results of steel-wool filter material are summarized in Table 10. In addition to dry testing, several spray arrangements were evaluated as part of the wet testing. The highest dust capture of 88% was achieved with vertically oriented sprays hollow-cone and flat sprays. Vertically oriented atomizing sprays with the filter also provided a very good dust suppression of 74.6%. Hence, this was the spray system selected for field demonstration since it utilized significantly less water.

Field Demonstration

The selected fiberglass material and a 1/8-inch thick steel-wool filter were demonstrated in the field. Tests were conducted in the production shaft area of a central Illinois mine. Dust levels as measured by a PDR in this area were 13.5 mg/m³. Even though there were no occupations operating in this area or downstream of this area, the high dust levels was a cause for concern due to dust depositions in the downstream areas. The mine had a spray system installed which was only marginally effective in reducing the dust concentration down to 11.1 mg/m³ as measured by the PDR.

The project team conducted the filter demonstration in this area using a fiberglass filter operating dry and a steel wool filter operating dry as well as in the presence of sprays. The dry fiberglass filter reduced the respirable dust as measured by gravimetric sampling down to 3.2 mg/m³ (corresponding PDR value of 5.6 mg/m³). This filter did not present a large resistance to air flow as measured by the insignificant change in air flow after introduction of the filter. When a steel wool filter was tested in the dry mode, the dust levels downstream were reduced to 2.1 mg/m³ (PDR – 3.9 mg/m³). This represented a 37% dust capture as measured by the difference in the upstream and downstream dust concentrations obtained from gravimetric sampling. This filter however reduced air flow by 19% after introduction and 3 hours of operation. When water sprays were used in front of the steel wool filter a 51% reduction in dust was achieved with the measured downstream dust concentrations at 0.95 mg/m³ (PDR – 3.0 mg/m³). This superior dust capture is related to the use of sprays which when combined with the filter provide the residence time required to wet the dust. Due to the presence of water which kept the filter clean, absolutely no reduction in air flow resulted from the installation of this filter. The results of all these tests are summarized in Table 11.
Table 9. Laboratory airflow and dust capture tests for selection of a suitable fiberglass material for field demonstration. Dust concentrations were measured by PDR.

<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>Fiberglass 1</td>
<td>421</td>
<td>244</td>
<td>228</td>
<td>0.00734</td>
<td>53</td>
</tr>
<tr>
<td>Fiberglass 2</td>
<td>421</td>
<td>238</td>
<td>215</td>
<td>0.00758</td>
<td>58</td>
</tr>
<tr>
<td>Fiberglass 3</td>
<td>421</td>
<td>236</td>
<td>200</td>
<td>0.00752</td>
<td>58</td>
</tr>
</tbody>
</table>

C/S Area: 1.52 ft², ** P.U. - Practical Units

Table 10. Laboratory testing of 1/8-inch thick steel-wool filter.

<table>
<thead>
<tr>
<th>Test</th>
<th>Air Flow (cfm)</th>
<th>Pressure Drop (in. wc)</th>
<th>Downstream Dust Conc. (mg/m³)</th>
<th>Dust Reduction (%)</th>
<th>Water Usage (gpm)</th>
<th>Test Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7422</td>
<td>1.07</td>
<td>7.53</td>
<td>-</td>
<td>-</td>
<td>Free Flow</td>
</tr>
<tr>
<td>B</td>
<td>6826</td>
<td>4.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Free Flow with Filter</td>
</tr>
<tr>
<td>C</td>
<td>6510</td>
<td>6.15</td>
<td>0.84</td>
<td>88.8</td>
<td>3.3</td>
<td>Dust Measurements with Filter and Vertical Sprays - HC and Flat 3 vertical hollow cone sprays @ 30psi (0.78 gpm/spray) at 32” &amp; 1 vertical flat spray @ 40psi at 12” (1 gpm)</td>
</tr>
<tr>
<td>D</td>
<td>6901</td>
<td>3.97</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Free Flow with Filter</td>
</tr>
<tr>
<td>E</td>
<td>6333</td>
<td>4.34</td>
<td>4.14</td>
<td>45.0</td>
<td>3.6</td>
<td>Dust Measurements with Filter and Horizontal FC Sprays 3 horizontal full cone sprays @ 40psi (1.2 gpm/spray) at 7”</td>
</tr>
<tr>
<td>F</td>
<td>6717</td>
<td>4.96</td>
<td>1.92</td>
<td>74.6</td>
<td>0.9</td>
<td>Dust Measurements with Filter and Vertical Atomizing Sprays 3 1/4 LNN18 atomizing sprays (0.9 gpm/spray) @ 40psi in same location as test E</td>
</tr>
<tr>
<td>G</td>
<td>7271</td>
<td>0.90</td>
<td>3.16</td>
<td>58.0</td>
<td>0.9</td>
<td>Dust Measurements with only Horizontal Atomizing Sprays as in Test F</td>
</tr>
</tbody>
</table>
Table 11. Summary of demonstration of filter panels for dust control at a central Illinois mine.

<table>
<thead>
<tr>
<th>Test/Filter Material</th>
<th>Test Duration (min)</th>
<th>Upstream Dust Conc. mg/m³</th>
<th>Downstream Dust Conc. mg/m³</th>
<th>Reduction in Dust (%)</th>
<th>Reduction in Airflow (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine Sprays</td>
<td>15</td>
<td>(13.5)</td>
<td>(11.1)</td>
<td>18%</td>
<td>0%</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>290</td>
<td>3.5 (8.2)</td>
<td>3.2 (5.6)</td>
<td>11%</td>
<td>0%</td>
</tr>
<tr>
<td>Steel Wool – Dry</td>
<td>173</td>
<td>3.3 (6.9)</td>
<td>2.1 (3.9)</td>
<td>37%</td>
<td>19%</td>
</tr>
<tr>
<td>Steel Wool - Wet</td>
<td>75</td>
<td>1.95 (6.3)</td>
<td>0.95 (3.0)</td>
<td>51%</td>
<td>0%</td>
</tr>
</tbody>
</table>

CONCLUSIONS AND RECOMMENDATIONS

This research focused on improved dust control in underground Illinois coal mines. The dust control research focused on spatial evaluation of dust in a super-section, demonstration of a comprehensive dust control package for a continuous miner, development of a CFD model for a single entry and the demonstration of a low-cost dust control technology. Highlights of this research are presented below.

- 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 dust control inventory of a super-section indicated that 60% of the dust exposure of the ram car operator occurs away from the face. A major portion of this dust exposure occurs at the feeder. This new finding indicates that research efforts in the future need to be devoted to dust control at the feeder to reduce this occupational dust exposure.

- The comprehensive dust control package which included modified scrubber and modified spray system was demonstrated at a central Illinois mine. Side-by-side comparisons with the regular miner indicated a 62%, 38% and 19% dust reduction at the miner operator, ram car operator and the return locations. These results reconfirm similar results obtained earlier with the modified spray system developed by the authors.

- A low-cost dust control filter technology was demonstrated in the production shaft area of a central Illinois mine. Earlier efforts by the mine using water sprays were only able to reduce the dust in this area by 18%. The wet and dry steel-wool filter tested by SIU researchers was able to successfully reduce dust in this area by 37% and 51% without offering any significant resistance to air flow. This technology could have several applications in Illinois coal mines.

- CFD modeling studies incorporating scrubber have indicated that the scrubber increases airflow in the face area. The scrubber also alters the airflow patterns in the face area to positively (reduce) the impact of dust on the miner and ram car
operator occupations. Increase in airflow at the roof level due to the scrubber indicates that the ignition probability would be reduced.

- With respect to the optimum scrubber capacity, the results indicate that higher scrubber capacities are desirable only if the line curtain can bring in air to the face which is in excess of the scrubber capacity.

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REFERENCES

DISCLAIMER STATEMENT

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