ABSTRACT

The overall goal of this project is to develop technologies that would reduce underground coal production cost by 20%. This report summarizes studies performed in Task 3 of this project: Developing an Education Program for Reducing Out-of-Seam Dilution (OSD). The Coal Industry Research Steering Committee identified reduction of OSD as a high priority area to achieve the desired cost reduction.

This task involved three subtasks; 1) Determine geotechnical properties of immediate roof and floor strata from different mines from dilution point of view, 2) Perform simulations to evaluate mining cycle delays associated with OSD and their relative importance from productivity and cost points of view, and 3) Develop concepts for minimizing dilution in concert with industry professional and MSHA.

A compilation of geotechnical data for roof and floor strata from Illinois mines indicated that 1) Immediate floor strata are generally much weaker ($C_o = 130-2940$ psi) as compared to immediate roof strata ($C_o = 361-4719$ psi), 2) Bulk density of immediate floor strata is about 10% lower ($94-164$ pcf) than immediate roof strata ($148-164$ pcf), and 3) Immediate floor strata are much more sensitive to water than immediate roof strata.

The simplified mathematical model of dilution developed during a previous ICCI project was modified to include in-seam dilution (ISD). The model was then integrated with the SSP model for production estimation and a cost model for estimation of face and out-bye production costs to study impacts of dilution. The estimated cost of dilution varies $2-4 per clean ton depending upon seam thickness and plant recovery. Sensitivity analyses and mathematical modeling showed that OSD is a critical component of the overall cost structure. Even a small reduction (2-inch) in OSD can help a mine improve its profitability.
EXECUTIVE SUMMARY

This report presents the results of research completed in Task 3: Developing an Education Program for Reducing Out-of-Seam Dilution (OSD). This task is part of the project “Reducing Underground Production Costs through Enhanced Face Productivity” whose overall goal is to develop technologies that would reduce underground coal production cost by 20%. While more than half of the cost of a ton of coal goes towards the actual mining process around the face area, the costs associated with conveying and processing the coal and waste disposal are also significant. Controlling these “out-by” costs begins at the face, by controlling what is mined. Mining, conveying, processing, and disposal of processing waste costs decrease when OSD is reduced. In short, reducing OSD has a pervasive impact on total mining cost. The project team estimates that out-of-seam dilution costs range from $2 to $4 per clean ton based on 65% average recovery in a processing plant. It should be emphasized that OSD related cost can be minimized but cannot be eliminated.

Controlling OSD has benefits that extend throughout the production process, starting with mining to shipping product to the customer and management of coal processing wastes. In addition, there are also significant energy savings as a result of reducing OSD. This task focused efforts in three distinct areas. The summary results in each area are presented below.

Task 3.1 - Determine geotechnical properties of immediate roof and floor strata from different Illinois mines from dilution point of view.

This task compiled geotechnical properties data for immediate roof and floor strata important from OSD point of view. These included strength, water sensitivity, and bulk density. Analysis of the data indicated that 1) Immediate floor strata are generally much weaker ($C_o = 130-2940$ psi) as compared to immediate roof strata ($C_o = 361-4719$ psi), 2) Bulk density of immediate floor strata is about 10% lower (94-164 pcf) than immediate roof strata (148-164 pcf), and 3) Immediate floor strata are much more sensitive to water than immediate roof strata.

Task 3.2 - Perform simulations to evaluate delays associated with mining dilutions and their relative criticalness from productivity and cost points of view.

The simple mathematical model of dilution developed in an earlier ICCI project was modified to include in-seam dilution (ISD). Sensitivity analyses were then performed to identify relative importance of different variables from production and cost points of view.

The simplified model above was integrated with the SSP model and the production cost model developed at SIU. The geotechnical data above was used in simulation and sensitivity analyses studies using the SSP model to find changes in mining cycle times and the delays associated with mining dilutions. The premise of this evaluation was that cutting of harder roof would take longer time as compared to weaker coal. The density of
the roof and floor strata would also impact the net carrying weight of the shuttle car, as the dilution material would occupy lesser volume as compared to coal. The available time to cut coal would be increased if OSD was reduced. The production costs of the mine panel as well as the out-byce costs were assumed variable depending on the type of equipment used and the amount of dilution.

The model simulation showed that the effect of reduced OSD on the profitability of a mine is non-linear. This is explained by a stepwise reduction in the number of trips made by the cars as the amount of OSD is reduced. It also indicates that a 2-inch decrease in OSD at one mine in central Illinois can help increase the amount of coal cutting time by 4.3%.

Task 3.3 - Develop concepts for minimizing dilution in concert with industry professionals and MSHA.

Based on the above analyses, interactions with mining professionals, and extensive literature review, a few concepts for reducing OSD were identified.

A necessary component of an automated coal mining method should be seam-following technology. This is usually achieved through detecting the coal-rock interface (CID). There are numerous types of CID technologies that are being employed and tested around the world. These include natural gamma radiation (NGR), vibration, infrared, optical / video sensors, radar, and pick force.

NGR CID works on the principle that shale, clay, silt, and mud have higher levels of naturally occurring radioactivity than coal. This is due to presence of minute quantities of radioactive potassium (K-40), uranium, and thorium. The attenuation of the NGR towards the coal can be used to measure the thickness of the coal between the sensor and the rock interface. The measured NGR decreases exponentially as a function of coal thickness.

Vibration based CID detects the changes in vibration characteristics during cutting of coal and associated roof and floor strata. Infrared CID principle is that different types of strata release different amounts of infrared radiation. Optical CID uses the difference in reflectivity of coal and associated strata to distinguish between them. Radar based CID works on the difference in density of the rock and coal. Pick force CID measures changes in the force exerted on one or more of the picks on a continuous miner due to cutting of different types of rock.

Horizon Sensing (HS) technology using radar, based on coal-rock interface detection (CID) techniques, has been experimented in the field. Stolar Research Corporation, New Mexico is a leader in this field and they have installed HS on several longwall shearsers and continuous miners in the USA, including one longwall shearer and one continuous miner in Illinois. Based on input from industry, the HS appears to do a fair job of detecting the interface but there is considerable noise in the collected data. The current HS technology performance is not optimum. Some of the recent improvements in the HS
involve better signal to noise ratio, void detection ahead of mining, and improved range and discrimination.

The project team has developed a simple concept to control a continuous miner to stay within the coal seam. Preliminary discussions with one coal company indicate potential for the concept with possible intellectual property rights. Additional meetings to discuss the concept with the company and Joy Machinery are planned in September.

The feasibility of separating dilution underground and placing it in mined-out areas also has been discussed with one mining company. MSHA current regulations on underground placement of dilution seem to be a major deterrent to this concept.

The mining industry is keen to develop strategies for reducing OSD. Most companies contacted this year still want to start with an education program on OSD that emphasizes production and economic impacts. Some companies believe that a “bonus” based on OSD reduction could be developed to motivate production workers to minimize OSD.
OBJECTIVES

The objective of the overall research program “Reducing Underground Production Costs through Enhanced Face Productivity” was to develop and demonstrate advanced mining technologies that will improve face productivity and reduce production cost by 20%. Controlling out-of-seam dilution (OSD) was identified as a high priority research topic towards achieving this objective. During a previous project on this subject funded by ICCI (Chugh et al. 2003), the project team collected dilution related data, discussed dilution minimization approaches with coal mines, and developed a simplified approach to analyzing the cost of OSD. One of the recommendations of the study was that an education program on OSD should be developed that emphasizes its financial impacts.

The Task 3 in 2003-2004 project was an attempt to develop some of the elements of such an education program for reducing out-of-seam dilution. More specifically, the goals of this task were: 1) Further develop the impact of OSD on mining cycle and production cost, and, 2) Develop concepts for minimizing dilution. Towards achieving these goals the task was divided into four distinct sub-tasks described below.

Task 3.1 - Determine geotechnical properties of immediate roof and floor strata from different mines from dilution point of view.

This task involved development of geotechnical properties data for immediate roof and floor strata which was important from OSD point of view. These included strength, water sensitivity, and bulk density characteristics of the roof and floor strata.

Task 3.2 - Perform simulations to evaluate delays associated with mining dilutions and their relative criticalness from productivity and cost points of view.

The geotechnical data generated in Task 3.1 was used in simulation and sensitivity analyses studies using the SSP model to find the mining cycle times and delays associated with mining dilutions.

Task 3.3 - Develop concepts for minimizing dilution in concert with industry professional and MSHA.

Based on the above analyses, interactions with mining professionals, and an extensive literature review, concepts for reducing OSD were developed.

Task 3.4 – Reports

This task would develop concise but comprehensive reports suitable for use by the industry professionals.
INTRODUCTION AND BACKGROUND

As mechanization developed in the coal industry, the productivity of the coal miner increased dramatically. Over the past two decades, the quest has continued to develop higher production methods and equipment. These improvements have led to record production levels and lower production costs enabling the industry to remain competitive in a rapidly changing marketplace. However, not all of the changes have been positive. While productivity has risen dramatically, the quality of the product mined at the face has steadily declined. Part of the reason for this decrease in quality is that mines are working lower quality seams as better reserves are depleted. But it is also true that the mines are removing a higher percentage of out-of-seam materials (roof and floor) than before. The push for higher production levels has, in many cases, caused operations to lose their focus on the quality of the material being mined. Some of the dilution is related to creating operating head room while mining thinner seams.

Figures 1 and 2 show dilution due to mining of immediate roof and floor strata associated with a coal seam. In Illinois, only 60%-70% of the run-of-mine coal is of marketable quality for power generation. The remaining 30%-40% (representing dilution) has very low heating value (~1,000 Btu/lb). The mining of rock bands in the coal seam and associated immediate roof and floor strata, represent in-seam and out-of-seam dilution (OSD), respectively. Since only OSD may be controlled, most of the discussion here refers to OSD only. OSD affects production cost and profitability of a mining enterprise because only the marketable coal represents the revenue stream. Almost all discussions with mining professionals in Illinois indicated that the OSD facet of mining and its impacts on production cost are not well understood. It is only in the last 2-3 years that industry is reviewing ways to reduce OSD. There is a potential to reduce production cost by 5%-10% if OSD cost is significantly reduced.

Sources of Dilution

The sources of dilution may be divided into the following three main classes (Noppe, 2003): 1) Primary Dilution, 2) Secondary Dilution, and 3) Tertiary Dilution.

Primary dilution: This includes cutting of the immediate floor or roof (accidental or planned) strata by the continuous miner. The reasons for such dilution range from controlling roof falls to mining of a minimum height for operator comfort, or equipment size. This type of dilution is very common in Illinois mines due to lower seam heights (4.5–5.5 feet). Poor roof conditions generally exacerbate the problem. Figure 3 shows the stratigraphic distribution in a typical Illinois mine with the effects of dilution on coal quality.

Secondary dilution: This includes slabbing or break-up of the roof or floor during mining and hauling, and the subsequent loading of this material together with the coal (rather than being hauled to mined-out areas). This form of dilution is very common in weak roof and floor conditions which are very common in Illinois mines.
Tertiary dilution: This includes waste material loaded with the coal during section-cleaning operations. An example is incorporation of waste material from the longwall gate roads (continuous miner generated material) with the coal mined from a retreating longwall face.
Continuous miner and shuttle car movement in roadways also results in the break-up of the floor strata behind the actual advancing face. This is a potential source of secondary and tertiary dilution. This is common around the center of the travel and haulage roadways and is particularly severe at intersections.

Figure 3. Typical stratigraphic section of a coal seam in Illinois (modified after Stolarczyk and Wattley, 2002).

**Causes of OSD**

OSD in run-of-mine (ROM) coal can be linked to weak roof and floor materials, seam height, etc. Each mining operation has different issues. However, in most cases, the potential exists to significantly improve profitability through reduction in OSD. Chugh et.al. 2003, discussed the most common causes of OSD in a previous report. A brief summary is included here for the reader. The most common causes of OSD are:

1. Poor roof and floor conditions – These conditions are generally out of the control of the mining operation and are a product of the geology of the region mined.
2. Low seam height conditions – Due to typically marginal seam thickness (4.5–5.5 feet), the operators cut into roof and floor materials to gain height for operator comfort and equipment clearance. This results in increased OSD.
3. Larger and heavier equipment – Although larger, heavier and more powerful equipment have increased production and productivity, they have increased OSD. This is due to: 1) Clearance requirements of the equipment, 2) Breaking up of weak floor strata which must be loaded out with coal.
4. High production systems – High production systems generally inhibit the operator’s ability to see and operate the machine as cut depth increases. Improved haulage
systems behind the miner allow less available time for the operators to position the machines and check their horizon control. Thus, technology improvements have generally increased OSD.

5. Changes in priorities – Processing operators perceive that mining a clean product was no longer important. As the focus on increasing productivity has continued, OSD has received less attention.

**Benefits of reduced OSD**

Dilution impacts every facet of the mining operation as shown in Figure 4. Some of the issues related to each facet are also shown in the figure.

![Figure 4. Dilution and associated costs/issues in different parts of the mining cycle.](image)

1. **Face costs** – Reduced wear and tear on miner bits can reduce miner operation cost.
2. **Dust control** – Dust generated by cutting OSD can lead to silicosis (due to higher silica content in rocks) in miners as well as impair visibility in the face area.
3. **Belt conveyors** – Hauling OSD material consumes capacity that can be otherwise used to transport saleable material. Also OSD typically contains a high percentage of clay, which is difficult to remove from the belt and creates the carry back problem.
4. **Preparation plant** – Apart from a reduction in total volume processed, the most significant gain would be in controlling the amount of fines produced. Reducing the OSD fines reduces chemical cost, and increases plant efficiency.
5. **Waste disposal** – Reducing OSD will reduce the overall waste disposal cost.

The important elements of dilution cost include: 1) ISD (partings, cleat fillings), 2) OSD (cutting of roof and floor, roof falls in the face area during mining, roof falls out-by of
the mining area, 3) Impacts of dilution on recovery, 4) Processing cost for dilution, 5) Dilution disposal cost, and, 6) Coal quality penalties from the customer.

The important factors affecting OSD include geologic factors, engineering and planning factors, and operational factors (Chugh et al. 2003).

1. Geologic factors include: 1) Structural topography of the coal seam, 2) Thickness of coal seam, 3) Nature of roof and floor strata (immediate), 4) Sensitivity of roof and floor strata to moisture, 5) Geologic anomalies (folding, faulting, intrusions, shear zones), 6) Ground behavior during mining, and, 7) Presence of water in mining areas.

2. Engineering and planning factors include: 1) Characterization of roof and floor topography, 2) Selection of mining height in relation to seam height, 3) Design of mining layout in relation to preexisting stress field, 4) Depth of mining cuts, 5) Coordination of mining and bolting cycles or installation of support in the mining cycle (ground reaction) characteristics, and, 6) Selection of appropriate equipment.

3. Operational factors include: 1) Continuous miner operator training, 2) Roof bolter operator training, 3) Dust control in the face area, 4) Rate of face advance, 5) Depth of mining cuts, 6) Control of water in mining areas, and, 7) Cut-sequence in the mining layout.

To reduce amount of dilution at source, Noppe (2003) proposes to first identify the sources of dilution. This should be done with regard to the types and proportions of dilution (roof, floor, waste etc.) and the distribution of dilution areas. Once this has been achieved, the mine must consider ways to reduce dilution at the source. Approaches may include education (awareness) of production personnel, redefining cutting and/or loading procedures, and minor or major design changes to mining equipment.

Productivity is still the largest factor in the economic analysis of a coal operation and there are many of the opinion that in order to improve mine yield, production and productivity must be sacrificed. The goal of this project is to develop strategies that will not only accomplish a reduction in out-of-seam dilution, but will do so without adversely impacting overall productivity. It is necessary to accomplish this goal in order to maximize the benefit from the reduction in out-of-seam dilution.

EXPERIMENTAL PROCEDURES

The overall approach consisted of: 1) Developing methodology for assessing cost and profitability impacts of dilution, 2) Identifying variables affecting dilution, 3) Developing geotechnical data on coal, roof and floor strata, 4) Performing simulations to identify effects of dilution on equipment cycle times and production cost, and 5) Identifying solutions to minimize dilution.
**Task 3.1 - Determine geotechnical properties of immediate roof and floor strata from different mines from dilution point of view.**

Developing geotechnical data for immediate roof and floor strata was an important task in this study. During visits to two mines during early stages of this project, small samples of immediate roof and floor strata were brought to the laboratory for testing. Attempts were made to cut samples for testing. However, meaningful size samples could not be produced and limited testing showed considerable variability. Therefore, another approach was adopted to develop this data. Several mines in Illinois were asked to provide geotechnical data on the cores obtained during exploratory drilling, or plate loading test data on immediate floor. This task was done to assess relative importance of roof and floor strata in OSD.

**Task 3.2 - Perform simulations to evaluate delays associated with mining dilutions and their relative criticalness from productivity and cost points of view.**

A mathematical model was developed in a previous project funded by ICCI to understand the problem of OSD (Chugh et.al. 2003). The model ignored ISD such as partings in a coal seam. Therefore, during this study as part of Task 3.2, the developed model was modified to include the effect of in-seam partings. A brief description of the modified model follows the description of SIU-Suboleski Production Model (SSP model). The model was used to define the effect of OSD on production and profitability of a mining operation. The modified OSD model was integrated with the SSP model and SIU production cost model to assess the productivity and production cost gains associated with reduced OSD.

**Description of SSP Model**

The SSP model is a simple deterministic worksheet for estimating production potential of a mining system. It determines the expected unit shift production rate by calculating the mining rate averaged over two or three crosscuts of advance (belt move to belt move). The model is divided into three worksheets: data section, calculation section, and output section. The data section consists of describing mine plan parameters including change-out distance, haul distances, depth of cut, and number of cars used for each cut, loading rates, dump rates etc. In the calculation section, the model determines the time taken in each cut for loading, hauling, dumping, and changing out haulage units and adds them together with expected delays to get the total cycle time for a particular cut. The production per shift is determined by multiplying the mining depth, height, and width with the density of coal. The production rate is determined by dividing shift production by the total cycle time.

The output section provides a brief summary of calculated production rates as well as average load times, change-out times, and wait-on-car times on a per cut and a per shift basis. A more detailed discussion of SSP is given elsewhere (Moharana, 2004).
OSD Model

1) The OSD model incorporates coal seam thickness, roof and floor and in-seam dilution (ISD) thickness, and bulk density of coal, roof, floor strata and ISD (Figure 5). Tonnages of coal and roof, floor and ISD are calculated separately and their effect on production, linear advance per shift, and profitability are determined. The developed equations are given below.

**OSD Model**

![Diagram](image)

Figure 5. Simplified mathematical model for studying dilution

In the figure above, let:

- \( X = \text{linear advance/shift (ft)} \)
- \( w = \text{opening width (ft)} \)
- \( h = \text{seam height (ft)} \)
- \( t_{\text{roof}} = \text{roof dilution (in)} \)
- \( t_{\text{floor}} = \text{floor dilution (in)} \)
- \( t_{\text{is}} = \text{in-seam dilution (in)} \)
- \( t = \text{total dilution (in)} \)
- \( \gamma_{\text{roof}} = \text{average unit weight of roof dilution (pcf)} \)
- \( \gamma_{\text{floor}} = \text{average unit weight of floor dilution (pcf)} \)
- \( \gamma_{\text{is}} = \text{average unit weight of in-seam dilution (pcf)} \)
- \( \gamma_c = \text{unit weight of coal (pcf)} \)
Let,
\[ \gamma_{\text{roof}} = \text{Average unit weight of roof dilution (pcf)} \]
\[ \gamma_{\text{floor}} = \text{Average unit weight of floor dilution (pcf)} \]
\[ \gamma_{\text{is}} = \text{Average unit weight of in-seam dilution (pcf)} \]
\[ \gamma_{\text{c}} = \text{Unit weight of coal (pcf)} \]
\[ t_{\text{r}} = \text{Roof dilution (inches)} \]
\[ t_{\text{f}} = \text{Floor dilution (inches)} \]
\[ t_{\text{is}} = \text{In-seam dilution (inches)} \]
\[ t = \text{Total dilution (inches)} \]
\[ P_s = \text{ROM production / shift (tons / shift)} \]
\[ R = \text{Recovery (\%)} \]
\[ r = \text{Recovery of clean coal from in-seam coal (\%)} \]
\[ d = \text{Depth of cut (feet)} \]
\[ w = \text{Average entry width (inches)} \]
\[ H = \text{Average seam height (inches)} \]
\[ N = \text{Number of shifts/day} \]
\[ D = \text{Number of days/year} \]
\[ C_p = \text{ROM production cost (face) ($ / ROM ton)} \]
\[ C_o = \text{ROM production cost (out-bye) ($ / ROM ton)} \]
\[ C_{\text{PR}} = \text{Processing cost ($ / ROM ton)} \]
\[ C_w = \text{Waste disposal cost ($ / waste ton)} \]
\[ C_A = \text{Administrative overhead ($ / ROM ton)} \]
\[ S = \text{Selling price of clean coal per ton ($ / clean ton)} \]
\[ L_{\text{h}} = \text{Capacity of haulage units} \]

Total dilution thickness, \( t \) = \( t_{\text{r}} + t_{\text{f}} + t_{\text{is}} \) \hspace{1cm} (1)

Recovery, \( R \) = \( \frac{\text{Clean Coal Tons}}{\text{Raw Coal Tons}} \)

\[ = \frac{\text{In - seam Coal Tons} * r}{\text{Roof Dilution} + \text{Floor Dilution} + \text{In - seam Dilution}} \]


\[ r \times (w \times d \times (h - t_i) \times \gamma_c) \]
\[ \frac{1}{(w \times d \times t_i \times \gamma_i) + (w \times d \times t_r \times \gamma_{roof}) + (w \times d \times t_f \times \gamma_{floor})} \]
\[ r \times (h - t_i) \times \gamma_c \]
\[ (t_i \times \gamma_i + t_r \times \gamma_{roof} + t_f \times \gamma_{floor}) \]

\[ \text{Average advance / shift (A)} \]
\[ = \left[ \frac{(PS \times 2000 \times 1728)}{(w \times (h - t_{is}) \times \gamma_c) + (w \times t_{is} \times \gamma_{is}) + (w \times t_f \times \gamma_{floor}) + (w \times t_{roof} \times \gamma_{roof})} \right] / 12 \text{ feet} \]

\[ \text{Clean coal/shift } (C_c) = P_s \times R \text{ tons} \]

\[ \text{Estimated clean coal / year } (C_{yr}) = C \times D \times N \text{ tons/year} \]

\[ \text{Effective working Days, } D = \]
\[ \text{Days in a year} - (\text{Weekends} + \text{Holidays} + \text{Belt move time} + \text{Down time}) \]

\[ \text{Production cost (clean coal) / shift } (C_{Pshift}) = P_s \times (C_p + C_o + C_{PR} + C_A) + (P_s (1 - R) \times C_w) \text{ $/ton} \]

\[ \text{Production cost / clean ton } (C_P) = \frac{C_{Pshift}}{C_c} \text{ $/ton} \]

\[ \text{Net Profit / Loss per year } (C_{Pyr}) = C_{yr} (S - C_P) \text{ dollars} \]

\[ \text{Change in profitability } (\%) \]
\[ = \frac{(C_{pyr, New \ Case} - C_{pyr, Base \ Case})}{C_{pyr, Base \ Case}} \times 100 \]

Let us define a factor ‘f’ called as the OSD cutting factor. It is defined as the ratio of the cutting rate of dilution to that of coal by the continuous miner.

Thus,
\[ C_c \]
\[ \text{Coal cutting rate} \]
\[ C_c \times f \]
\[ \text{OSD cutting rate} \]

\[ \text{Time required to cut in-seam } (t_{is}) = \frac{\text{In-seam Coal tons}}{\text{Coal Cutting Rate}} + \frac{\text{In-seam Dilution tons}}{\text{Dilution Cutting rate}} \]

\[ \text{Time required to cut OSD } (t_{os}) = \frac{\text{Out-of-seam Dilution tons}}{\text{Dilution Cutting rate}} \]

\[ \text{Total cutting cycle time } = t_{is} + t_{os} \]

Upon development of this model, the effect of several variables affecting dilution and their impact on production cost and enterprise profitability were analyzed. The analysis considered three cases:
Case 1: Car advance per shift is not constrained by the roof bolting cycle or other factors, i.e. raw coal production determined by system constraints is kept constant. (Constant ROM case)

Case 2: Linear advance per shift is constrained by factors external to the continuous miner, i.e. raw coal production of a mine varies but the clean coal production of the mine is kept constant to satisfy the market demand. (Constant clean coal case)

Case 3: The coal and OSD cutting rates are different. The analysis tried to determine the percentage of time expended for cutting OSD in a particular cut. This analysis assumed that the amount of clean coal production remains constant for a mine panel.

Task 3.3 - Develop concepts for minimizing dilution in concert with industry professional and MSHA.

The goal of this task was to identify feasible concepts that would potentially reduce OSD. An extensive literature review was conducted to review concepts which may have the greatest potential for success in reducing OSD in Illinois. The areas of literature review were coal interface detection (CID) technologies and local and global miner navigational techniques. Inputs were sought from industry professionals as well as MSHA. The project team held several discussion forums to conceive ideas and methodologies for reducing OSD.

RESULTS AND DISCUSSION

Task 3.1 - Determine geotechnical properties of immediate roof and floor strata from different mines from dilution point of view.

Bulk density, unconfined compressive strength (UCS), and moisture sensitivity are considered of primary importance from dilution point of view. A summary table (Table A.1) for the developed geotechnical data is given in Appendix A.

1) There appears to be no statistically significant difference between bulk density of immediate roof and immediate floor strata within one foot above or one foot below the seams mined in Illinois. The bulk density values for all strata range from 94-164 pcf. The floor strata within one foot below the coal seam has lower bulk density in the range of 94-164 pcf due to presence of organic matter or higher moisture, while the roof has bulk density ranging from 148-164 pcf, Figure 6(d).

2) There are significant differences in the compressive strength (UCS) of immediate roof strata (~ 361-4719 psi), and immediate floor strata (~130-2940 psi), Figure 6(c).

3) There are also significant differences in moisture sensitivity of immediate roof strata and immediate floor strata. The immediate floor strata strength typically drops by 50-75% upon wetting. Similar data for roof strata is only 10-20%.
Frequency distributions for moisture content of roof and floor strata (within 1 feet above and 1 feet below the coal seam) are given in Figures 6(a) and 6(b), respectively.

![Figure 6(a)](image1)

![Figure 6(b)](image2)

![Figure 6(c)](image3)

![Figure 6(d)](image4)

Figure 6. Frequency distributions of moisture content of roof strata (a) and floor strata (b); (c) unconfined compressive strength of floor strata; and, (d) bulk density of floor strata.

**Task 3.2 - Perform simulations to evaluate delays associated with mining dilutions and their relative criticalness from productivity and cost points of view.**

Dilution includes in-seam, out-of-seam, construction, and out-bye roof falls in the face area. Any dilution loaded on the belt and processed is included here. The first step was to estimate cost of dilution. A base case scenario was formulated for a mine in Illinois and all analyses were made in comparison to the base case.
Base Case Scenario (Initial Assumptions):

Height of the coal seam 60 inches
In-seam dilution 2 inches
Width of the opening 240 inches
Density of roof 140 pcf
Density of floor 120 pcf
Density of in-seam dilution 140 pcf
Density of coal 80 pcf
Production per shift 2,000 tons
Number of days per year 213
Number of shifts per day 3
Recovery 70%
Reject 30%
Estimated amount of coal discharged into ponds 5%
Estimated amount of coal misplaced in gob 3%
Actual dilution (= 30 – 8) 22%
Processing cost $ 1.40/ROM ton
Waste disposal cost $ 2.00/ ton of waste
Selling Price of Coal $ 20/ clean ton

This data was presented to coal industry professionals at the information transfer workshop in 2003. There was a general consensus on the stated assumptions. The OSD model was initially run with this data. Then the changes in the variables such as annual clean coal production, production cost per ton, and profitability as a function of dilution thickness, selling price of coal, and seam thickness were determined.

Chugh et. al. (2003) discussed this Case 1 (constant ROM case) in the final technical report submitted to ICCI. A summary graph of the impact of dilution thickness on production cost, for different seam thicknesses is given in Figure 7. A summary of the results is given below for typical OSD thickness of 14 inches.

- Cost of OSD is around $4-5/clean ton, assuming that all OSD can be eliminated.
- Decreasing dilution thickness by only two inches increases mine profitability by about 100% since profit margin is low for selling price of $20/ton.
- The gains due to reduction in OSD are more pronounced in thinner seams.
- The effect of dilution on profitability is highly sensitive to selling price of coal.
Figure 7. Effect of change in dilution thickness on production cost of clean coal.

The analysis of the combined OSD-SSP model for a battery ram car haulage system in an 11 entry walk between super-section is shown in Figure 8. This section uses two Joy 12 CM continuous miners, four battery ram cars and three double-boom roof bolters.

Figure 8. Eleven (11) entry-walk between super-section cut sequence

Figure 9 shows the cost of out-of-seam dilution per ton of clean coal. The relationship is generally linear with small steps representing a stepwise increase or decrease in the number of car trips based on production.
Figure 9. Impact of different dilution thicknesses on OSD cost per clean ton for various seam thicknesses

Figure 10 relates the production cost of clean coal with OSD thickness for \( f = 1.0 \). The analysis is shown for both 5-foot and 6-foot of coal seam thickness. A non-linear trend is observed due to stepwise increase or decrease in the number of trips based on production. A decrease in the number of car trips, based on reduced OSD, gives the graph a step drop in clean coal cost/ton.

Figure 11 shows the effect of reduced OSD on the profitability of a mine over the base case scenario. Again, a non-linear behavior in the profitability is seen for both cases. This is explained by the stepwise reduction in the number of trips made by the cars. A decrease in the number of car trips gives the graph a kink with a step increase in profitability. The increase in profitability for a mine with a 5-foot seam (lower seam height) is higher as compared to 6-foot (higher seam height) seam. This is due to higher percent increase in recovery for a unit reduction in dilution for lower seam height as compared to larger seam height.
Figure 10. Clean coal cost for various OSD thickness at varying seam heights.

Figure 11. Effect of reduced OSD on the profitability of a mine.

For the same reason stated above a non-linear behavior is again seen in Figure 12 which relates profitability to OSD for various selling prices of coal. The increase in profitability is much more pronounced when the selling price of coal is lower. This is due to the small profit margins for coal. Even a small drop in OSD can help a mine to operate in profit when selling price of coal is low.
To determine the sensitivity impacts of the OSD cutting factor ‘f’ which is unknown at present, simulations were conducted varying the factor ‘f’ between 0.75-1.1. The simulations assumed a coal seam thickness of 60 inches which includes 2-inch of in-seam dilution (ISD). The bulk density of coal, roof, floor and in-seam partings was assumed to be 80 pcf, 140 pcf, 120 pcf and 140 pcf, respectively. The percentage of time expended in cutting OSD is shown in Table 1. The base case consisted of 12-inches of OSD which included 3-inches of floor dilution.

The table shows that for an OSD cutting factor of 0.75 (i.e. the continuous miner cuts OSD at 0.75 times the rate of cutting coal) and for 12-inches of OSD, 26.3% of the continuous miner time is spent in cutting dilution. A 2-inch decrease in OSD reduces this time to 22% giving additional time for cutting in-seam material and OSD. This is one of the reasons why a small decrease in OSD can help the mine improve its profitability significantly. Other reasons include lower processing cost and lower waste disposal cost.
### Task 3.3 - Develop concepts for minimizing dilution in concert with industry professional and MSHA.

The goal of this task was to develop concepts that can be used for minimizing OSD in Illinois. This involved reviewing relevant literature, an analysis of questionnaire responses received in the previous year report, identifying simplified concepts that may have potential for use in Illinois.

**Review of Pertinent Literature**

The two most critical aspects of face navigation are the alignment of the continuous miner in the face area and guidance of the machine during cutting. It is also important that the miner have the ability to detect rock-coal interfaces, and to stay within the coal seam. Coal-rock Interface Detection (CID) technologies are employed for this purpose (Anderson, 1989). A brief description of the different CID technologies in use and in development is presented below.

**Coal-Rock Interface Detection (CID) Technologies**

An essential component of any automated coal mining method is seam-following technology. This is usually achieved through detecting the coal-rock interface. There are numerous types of CID technologies that are being employed and tested around the world. These include natural gamma radiation (NGR), vibration, infrared, optical / video sensors, radar, and pick force (Mowrey et al., 1992). Each of these methods has benefits and weaknesses that determine whether it can be utilized.

**Natural Gamma Radiation (NGR) based CID:** Natural Gamma Radiation (NGR) is being employed in commercial mining applications, with over one hundred and fifty units
around the world (Mowrey, 1991). This method works on the principle that shale, clay, silt, and mud have higher levels of naturally occurring radioactivity than coal. This is due to their content of minute quantities of radioactive potassium (K-40), uranium, and thorium. The attenuation of the NGR towards the coal can be used to measure the thickness of the coal between the sensor and the rock interface. The measured NGR decreases exponentially as a function of coal thickness. This method has many strong features that make it a viable option for use in automated mining operations. It can measure coal thickness readings from 2 to 50 centimeters. The indication is easily read from a display panel. This compact unit can be mounted on the miner itself, where it will not be in the way, and it is applicable in most seams. The most prevalent applications to date have been on longwall units.

There are a few inherent weaknesses in these systems that arise from the distribution of radioactive material in the seam. For example, NGR levels vary from seam to seam, requiring the units to be calibrated for each seam in which they will be used. Another minor problem is that the NGR levels can vary throughout a seam, depending on the levels of radioactive constituents that were present at the time of geologic deposition. Another problem that presents itself, at times, is that of rock partings, layers of rock that sometimes intrude into a continuous coal seam. These can show false seam boundaries to the unit by indicating a coal-rock interface within the seam. The applicability of such systems in Illinois may be limited since Black shale, a typical immediate roof bed, can have similar radiation properties as coal.

**Vibration Based CID**: When coal and rock are cut, different patterns of vibration are generated. By analyzing the vibrations produced, the sensor can detect when the machine has started cutting boundary rock instead of coal. The three types of vibrations that are studied include machine vibration, in-seam seismic, and acoustic vibrations (Mowrey, 1991).

The strengths and weaknesses of this method vary depending on which type of vibration that is being examined. When studying machine vibration, the sensors can be mounted on the machine itself so that the sensors are out of the way and need not be remounted as mining progresses. This method has good potential when adaptive signal discrimination technologies are used to help interpret the vibrations data. This system also gives immediate feedback when machine starts to cut rock so mining can be stopped when the machine senses roof. In-seam seismic and acoustic sensors must be attached to the coal itself, requiring the sensors to be remounted as mining progresses. This is inefficient, requires personnel to be at the working face to mount the sensors, and undermines one of the main reasons for having an automated mining method, i.e. to keep workers away from the production face. Hence, the in-seam seismic, or acoustic sensing methods are not practical in thin seams (Mowrey, 1991). Their applicability in Illinois conditions may be limited due to:

- Vibration based CID determines the interface based on difference in vibration characteristics. Vibration characteristics depend both on the hardness of the rock as well as fracture. Since fracture characteristics in Illinois are highly variable it
would be difficult to calibrate the machine for a particular seam. Frequent recalibration may also increase the cost of operation in addition to making it unreliable.

- The coal mined in Illinois is hard and in some cases has high compressive strength than the roof and floor materials. Thus the difference in the vibration frequency may be minimal.

**Infrared CID Technology:** Different types of strata release different amounts of infrared radiation while being cut. Infrared sensing devices can measure the values of infrared radiation emitted from the cutting zone. This method has distinct advantages that merit its further development. The radiation readings can be taken from a location behind the cutting drum, from a remotely mounted sensor, even when the drum is obscured by dust and water sprays. This method can be used under any type of roof, allows coal to be mined up to the roof, and yields an instantaneous response time (Mowrey, 1991).

**Optical / Video CID:** The concept used here is that different types of strata have different light reflectivity. This technology is not very accurate but is greatly improved by the addition of video cameras and image analysis equipment. These sensors, like the infrared sensors, can be remotely mounted and, with the appropriate video cameras, can see through moderate dust and water sprays. Heavy dust and water can cause problems. Another benefit of this system is that data obtained from the video systems can also be employed for guidance purposes (Mowrey et al., 1992). These CIDs may have limited application in Illinois conditions.

**Radar Based CID:** Radar based CID utilizes a single antenna, which transmits and receives Doppler radar pulses. A network analyzer is utilized to control frequency, and for signal analysis. The signals are attenuated as they pass through coal and bounce off the density interface of the confining rock. The attenuation of these waves can be interpreted to find the distance to that interface. This system has reliable accuracy and operates well under most roof conditions. Another application of this technology is that it may be used to measure the thickness of the ribs between adjacent holes in highwall mining. Some inherent problems with this system are that it does not work well in coals with wave dispersing properties, and it requires the transmitter to be within 10 cm of the coal (Mowrey and Ganoee, 1995).

**Pick Force CID:** This CID method measures changes in the force exerted on one or more of the picks on a continuous miner. The energy required to break differing types of rock results in varying forces being applied to any given pick. This phenomenon can be used to determine when the mining machine cuts into a different type of strata. This system could be conveniently integrated into the mining machine, keeping all of its components compact and protected. This system also gives instantaneous feedback when the miner leaves the seam. A commercial unit of this type has not been developed for advanced testing (Mowrey et al., 1992).
Application Experience of a CID technology in Illinois

National Mining Association and the Office of Industrial Technologies of the US Department of Energy have identified horizon sensing as a critical technology. Stolarczyk and Wattley (2002) describe application of CID in an Illinois mine for horizon sensing (HS). A commercial HS-3 unit was mounted on a Joy 12CM (Figure 13). This unit has a resonant patch antenna mounted on the cutter drum, and a digital signal processor (DSP). An inclinometer is mounted on the cutter drum to identify the cutter-head position at any time. A screen display permits the operator to selectively mine coal while minimizing dilution.

![Possible method of OSD control using CID](image)

Figure 13. Possible method of OSD control using CID (after Stolarczyk and Wattley, 2002).

Develop Concepts for Minimization of OSD

A review of questionnaire data on OSD from most mines in Illinois in 2003, and personal discussions with professionals in mining indicated the following:

1) There is a general consensus that HS technologies experimented to date do not provide good control on dilution.
2) Poor visibility in the face area during cutting does not allow for good horizon control by mining operators.
3) Current MSHA regulations on underground management of dilution rock, containing some coal, are not favorable from technical and economic points of
In addition, there is a potential for decrease in face productivity and increased risk in spontaneous combustion associated with underground management of dilution rock.

4) Almost all mine managers interviewed indicated that an educational program on OSD, that emphasizes financial impacts of OSD, would be a good first step.

5) In the earlier study on OSD (Chugh et.al., 2003), discussions on education program development centered around identification of best practices in different mines in Illinois. In the current study, there was consensus that OSD control studies should be performed in detail at one mine and lessons learned should form the foundation for the education program.

**Development of Concepts for Minimization of OSD**

In the course of this study, a simple concept has been conceived which may have potential for achieving a reduction in OSD. The concept utilizes seam isopach data to set and limit upward and downward angular motion of the cutter drum arm to touch roof and floor. An inclinometer, similar to that mounted on HS-3, can be utilized to check the mined seam thickness and comparison can be made with the isopach thickness estimate.

Since isopach data, is based on exploration holes that are sometimes 5000 feet apart, such data will be updated after each cut (20-40 ft) underground based on actual seam thickness measurements. Isopach data for the section being mined will be available on an on-board computer. After each cut, actual seam thickness will be input for the microprocessor to redevelop the isopach contours (using an appropriate function) to more accurately predict seam thickness over the next 20-40 feet. This predicted seam thickness will be mined by adjusting and limiting the upward and downward angular motion of the cutting drum arm.

This concept was disclosed to Mr. Hirschi and Mr. McGolden at a meeting at SIU. It has also been discussed with one mining company. Additional discussions of this concept with mining companies and Joy Mining Machinery are planned in September to evaluate feasibility of commercial implementation.

**CONCLUSIONS**

1. The developed simplified mathematical model of OSD (including ISD) provides a good understanding of the sensitivity of variables affecting production and profitability.
2. The coupled OSD and SSP models allow analysis of the impacts of OSD control on equipment delays, production and production cost.
3. The two items above can be effectively used as part of an education program to minimize OSD.
4. Seam thickness and selling price of coal are important variables affecting the impacts of OSD on profitability.
5. The models estimate OSD costs to vary from $3-5 / clean ton which represents about 15-30% of the current mining cost. Hence, OSD minimization should be pursued aggressively to make Illinois coal more competitive with Western coal.
RECOMMENDATIONS

1. Simplified concepts for OSD control should be considered for further development and evaluation.
2. A detailed study of OSD minimization should be pursued at one mine. The developed concepts should form the foundation for the OSD education program.

DISCLAIMER STATEMENT

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BIBLIOGRAPHY


### APPENDIX A

Table A.1 Geotechnical Data Developed for Immediate Roof and Floor Strata

<table>
<thead>
<tr>
<th>Mine #</th>
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<th>Sample location</th>
<th>Depth (ft)</th>
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<th>UCS, psi</th>
<th>Tensile strength, psi</th>
<th>Bulk Density,pcf</th>
<th>CMRR water sensitivity</th>
<th>Moisture content, as-received (%)</th>
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Note: CMRR water sensitivity was rated with a scale of 0 - 15 from not sensitive to severely sensitive
UCS: unconfined compressive strength; Avg: Average; SD: Standard Deviation
EQUIPMENT INVENTORY REPORT
April 1, 2003 through August 31, 2004

Project Title: REDUCING UNDERGROUND PRODUCTION COSTS THROUGH ENHANCED FACE PRODUCTIVITY
Task 3 – Developing an Education Program for Reducing Out-of-Seam Dilution

ICCI Project Number: 02-1/1.1A-1
Principal Investigator: Dr. Y. P. Chugh, Southern Illinois University
Other Investigators: A. Moharana, A. Patwardhan, M. McGolden, J. Hirschi, K. Thatavarthy, and M. Alam
Project Manager: Dr. Ronald Carty, Illinois Clean Coal Institute

LIST OF EQUIPMENT PURCHASED

No equipment was purchased from the project funds.
Project Title: REDUCING UNDERGROUND PRODUCTION COSTS THROUGH ENHANCED FACE PRODUCTIVITY

Task 3 – Developing an Education Program for Reducing Out-of-Seam Dilution

ICCI Project Number: 02-1/1.1A-1
Principal Investigator: Dr. Y. P. Chugh, Southern Illinois University
Other Investigators: A. Moharana, A. Patwardhan, M. McGolden, J. Hirschi, K. Thatavarthy, and M. Alam, SIUC
Project Manager: Dr. Ronald Carty, Illinois Clean Coal Institute

During the course of the project, the following paper related to Task 3 was presented.
