NITROGEN INJECTION IN PROGRESSIVELY SEALED LONGWALL GOBS AND THE
FORMATION OF A COMPLETE AND DYNAMIC SEAL

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Mining and Earth Systems Engineering).

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Methane ignition and spontaneous combustion of coal are two common ventilation hazards associated with longwall coal mining. Methane is a coal mine gas emitted from the surrounding strata and the seams themselves as part of the mining process. Methane is diluted by the mine ventilation system used to provide fresh air to the face. Methane air mixtures become explosive between the lower explosive limit of 5.5% methane and the upper explosive limit of 14% methane. Mixtures with higher methane contents will burn as a diffusion flame. Methane ignition has been the cause of several recent mine tragedies including the Upper Big Branch Mine explosion in April 2010 and the Pike River Mine explosion in November 2010. Spontaneous combustion is an exothermic reaction involving coal and oxygen. The initiation of spontaneous combustion is dependent on oxygen concentration and residence time in addition to other factors. If the heat from the reaction is not dissipated the heating can proceed to thermal runaway or a fire that may result in fatalities, equipment losses and or mine closure. Recent spontaneous combustion events have resulted in the temporary closure and loss of longwall equipment and reserves at the Elk Creek Mine from a fire that was discovered in January 2013 and the Soma Mine Disaster that resulted in over 300 fatalities from an explosion that is suspected to have initiated from a spontaneous combustion fire. The investigation is still on going.

The focus of this dissertation is to investigate the use of nitrogen to both reduce explosive gas volumes and to reduce the spontaneous combustion potential by diluting oxygen ingress behind the longwall shields. This research will investigate the quantity of nitrogen injection, the injection location and the method of face ventilation to determine the effectiveness of each variable in mitigating the hazards discussed above. The hypothesis is that a back return scheme in conjunction with progressive nitrogen injection creates a safer work environment than a traditional U-Type ventilation scheme in terms of both explosive gas and spontaneous combustion hazards.

Knowledge regarding the porous media distribution of the caved gob is required for modeling the gas distributions. Previous findings regarding porous media distribution of the gob and nitrogen injection are presented and discussed in a literature review. A geo-mechanical model was developed to determine the porous media distribution for an active longwall panel. A numerical fluid flow and gas dilution model was developed using the porous media distribution and utilized to study the validity of
the hypothesis. Nitrogen injection amount and location was varied for both U-Type and back return face ventilation schemes to determine the effectiveness of each on the desired hazard mitigation.

Important conclusions drawn from the research include the following findings. Porous media distributions are noticeably different for static panels compared to active panels simulated by utilizing a method of stepped extraction for the geo-mechanical model. These differences are especially apparent immediately inby the face. There is a point of diminishing returns for nitrogen injection quantity for both face ventilation methods. It was found that nitrogen injection closer to the face provides more diluting and inertization effectiveness than locations further inby. A back return with sufficient nitrogen injection directly inby the face provided the optimal dilution and inertization scheme. Although a back return increases oxygen ingress and creates a larger volume of explosive gas the oxygen can be diluted rapidly through a nitrogen induced, complete dynamic seal stretching from headgate to tailgate. In addition the explosive gas region is moved further inby and away from the active workings of the face in the back return scheme. These findings partially satisfy the hypothesis that implementing a back return provides a safer working environment compared to standard U-Type ventilation. The explosive potential risk has been reduced although spontaneous combustion indicator gases should be closely monitored and the nitrogen injection system well maintained due to the increased oxygen ingress.
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<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A$</td>
<td>Area (m$^2$)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Angle of Friction (degrees)</td>
</tr>
<tr>
<td>$K_o$</td>
<td>Base Permeability (m$^2$)</td>
</tr>
<tr>
<td>$K$</td>
<td>Bulk Modulus (MPa)</td>
</tr>
<tr>
<td>$p_c$</td>
<td>Cap pressure (MPa)</td>
</tr>
<tr>
<td>$a_p$</td>
<td>Center coefficient for general CFD variable</td>
</tr>
<tr>
<td>$c$</td>
<td>Cohesion (MPa)</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Cross Sectional Area (m$^2$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density ($\text{kg/m}^3$)</td>
</tr>
<tr>
<td>$\gamma_M$</td>
<td>Dilation dissipation ($\text{kg/m}^3$)</td>
</tr>
<tr>
<td>$x_i$</td>
<td>Distance in direction “$i$” (m)</td>
</tr>
<tr>
<td>$x$</td>
<td>Distance in x direction (m)</td>
</tr>
<tr>
<td>$y$</td>
<td>Distance in y direction (m)</td>
</tr>
<tr>
<td>$z$</td>
<td>Distance in z direction (m)</td>
</tr>
<tr>
<td>$\mu_{eff}$</td>
<td>Effective viscosity ($\text{Ns/m}^2$)</td>
</tr>
<tr>
<td>$\epsilon_{1,e}$, $\epsilon_{2e}$, $\epsilon_{3e}$</td>
<td>Elastic strain in direction “$i$” (m/m)</td>
</tr>
<tr>
<td>$a$</td>
<td>Empirical parameter for gob hardening (MPa)</td>
</tr>
<tr>
<td>$b$</td>
<td>Empirical parameter for gob hardening</td>
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<tr>
<td>$V_p$</td>
<td>Face advance rate (m/yr.)</td>
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<tr>
<td>$c_{Knothe}$</td>
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<tr>
<td>$d$</td>
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<td>$K_{Final}$</td>
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Form drag constant term ................................................................. $c_F$

Generation of k from buoyancy effects (kg/sm) .................................. $G_B$

Generation of k from velocity gradients (kg/sm) ................................. $G_k$

Generic form of dependent variable, Navier Stokes ........................... $\Phi$

Generic form of diffusive coefficient, Navier Stokes Equation .............. $\Gamma$

Generic form of source term, Navier Stokes Equation ........................ $S_\Phi$

Globally scaled residual of general CFD variable .............................. $R_\Phi$

Heat transfer (W) ............................................................................... $\dot{q}$

Hydraulic diameter (m) ................................................................. $D_h$

Inertial resistance factor ................................................................ $C_2$

Initial Subsidence ............................................................................. $W_o$

Interstitial surface area of the pores per unit of bulk volume (m$^2$) ........ $M_B$

Interstitial surface area of the pores per unit of solid material (m$^2$) .... $M_s$

Kozeny constant ............................................................................. $c_o$

Laminar Viscosity $(\text{Ns/m}^2)$ ......................................................... $\nu$

Length (m) ..................................................................................... $L$

Mass diffusion coefficient of species "k" (m$^2$/s) ............................... $D_k$

Mass fraction of species “k” ............................................................. $Y_k$

Maximum Skewness of CFD mesh .................................................. $q_{\text{max}}$

Minimum Skewness of CFD mesh ................................................... $q_{\text{min}}$

Modulus of the mean rate of strain tensor ........................................ $S$

Momentum loss in porous media (kg m/s) ........................................ $S_i$

Neighboring cell coefficient for general CFD variable ........................ $a_{nb}$
Nitrogen injection quantity (m³/s) ..........................................................
Particle diameter (m) ..............................................................................
Percentage of final subsidence, Peng (%) ..............................................
Permeability (m²) ....................................................................................
Plastic stiffness (MPa) ...........................................................................
Plastic volumetric strain (m³/m³) ............................................................
Plastic volumetric strain stiffness constant .........................................
Porosity (%) ...........................................................................................
Prandtl Number .....................................................................................
Pressure (Pa) ........................................................................................
Radius of major influence ...................................................................
Relaxation factor ................................................................................
Reynolds number ................................................................................
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Shear stress (MPa) .................................................................................
Skewness of an optimal mesh element ................................................
Source term contribution to general CFD variable ............................
Source term for species “k” (kg/s) .........................................................
Source term in direction “i”, Navier Stokes Equation ............................
Strain (cm/cm) .....................................................................................
Strength of standard 50mm laboratory rock sample (MPa) ................
Stress in direction “i” (MPa) .................................................................
Stress, MPa ...........................................................................................
Subsidence at time “t” (m) ....................................................................

Q_{NZ}
D_p
K_{Dyn}
k
K_p
\varepsilon_{v,p}
\zeta
n
PR
p
r
\alpha
R_e
G
\tau
q_e
b_S
S_y
S_u S_v S_w
\epsilon
\sigma_{50}
\sigma_1 \sigma_2 \sigma_3
\sigma
W(t)
Temperature (K) \( T \)

Time (seconds) \( t \)

Time coefficient, Peng (1/yr.) \( c_{Peng} \)

Turbulent dissipation \( \frac{kg}{m\cdot s} \) \( \epsilon \)

Turbulent dissipation transport coefficient \( \alpha_{\epsilon} \)

Turbulent kinetic energy \( \frac{kg}{m\cdot s} \) \( K \)

Turbulent kinetic energy transport coefficient \( \alpha_{K} \)

Turbulent Prandtl Number \( PR_{T} \)

Turbulent viscosity \( \frac{Ns}{m^{2}} \) \( v_{T} \)

Updated Bulk Modulus, double yield model (MPa) \( K_{New} \)

Updated Shear Modulus, double yield model (MPa) \( G_{New} \)

Value of general CFD variable after relaxation \( \Phi_{P,Actual} \)

Value of general CFD variable from prior iteration \( \Phi_{Old} \)

Value of general CFD variable in cell \( \phi_{p} \)

Value of general CFD variable in neighboring cell \( \Phi_{nb} \)

Velocity in direction \( "i" \) (m/s) \( u_{i} \)

Velocity in x direction (m/s) \( u \)

Velocity in y direction (m/s) \( v \)

Velocity in z direction (m/s) \( w \)

Viscosity \( \frac{Ns}{m^{2}} \) \( \mu \)

Volume \( m^{3} \) \( V \)

Volumetric flow rate \( m^{3}/s \) \( Q \)

Volumetric strain (cm/cm) \( \epsilon_{Vol} \)
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>Computational Fluid Dynamics</td>
<td>CFD</td>
</tr>
<tr>
<td>Commonwealth Scientific and Industrial Research Organization (Australia)</td>
<td>CISRO</td>
</tr>
<tr>
<td>Explosive Gas Zone</td>
<td>EGZ</td>
</tr>
<tr>
<td>Graphical User Interface</td>
<td>GUI</td>
</tr>
<tr>
<td>Gob Vent Borehole</td>
<td>GVB</td>
</tr>
<tr>
<td>Headgate</td>
<td>HG</td>
</tr>
<tr>
<td>National Institute for Occupational Safety and Health</td>
<td>NIOSH</td>
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<tr>
<td>Net Present Value</td>
<td>NPV</td>
</tr>
<tr>
<td>Reynolds-averaged Navier-Stokes</td>
<td>RANS</td>
</tr>
<tr>
<td>Rock Quality Designation</td>
<td>RQD</td>
</tr>
<tr>
<td>Spontaneous Combustion</td>
<td>Spon Com</td>
</tr>
<tr>
<td>Tailgate</td>
<td>TG</td>
</tr>
<tr>
<td>Textual User Interface</td>
<td>TUI</td>
</tr>
<tr>
<td>User Defined Function</td>
<td>UDF</td>
</tr>
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ACKNOWLEDGEMENTS

First and foremost I would like to thank my family for all their support and understanding through the years, which has extended well beyond my pursuit of a doctoral degree. I would particularly like to thank my parents for encouraging me to pursue engineering. They are both engineers and were able to share experience and guidance that has helped me achieve many academic, professional and personnel accomplishments.

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xx
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DEDICATION

To my family for their endless support and understanding that ensured this work was completed.
CHAPTER 1
INTRODUCTION

The modeling research presented is meant to build upon previous work completed by Dr. John Grubb (Grubb, 2008) and fellow researcher Dr. Dan Worrall (Worrall, 2012). Their initial work serves as the foundation upon which this work is constructed. Grubb evaluated the economic feasibility of spontaneous combustion prevention measures using a cost benefit analysis approach. Worrall developed an explosive gas algorithm used to evaluate and present explosive gas mixtures in terms of location and relative size. A modular meshing technique developed by Gilmore (2014) made the parametric studies carried out in this dissertation possible. This dissertation, along with past and present research regarding gob gas hazard detection at the Colorado School of Mines, has the potential to save the lives of miners, and in doing so serves the interests of the underground coal mining industry as well as the general public.

1.1 Problem statement

The mining industry relies on advanced mine wide monitoring systems to detect ventilation hazards. Current monitoring systems can only detect localized gas distributions. Even advanced monitoring systems such as tube bundle systems are unable to collect data from the interior of the gob. This region may contain hazards associated with methane and spontaneous combustion that are undetectable using current monitoring systems until the situation has become severe. For example, due to limited information regarding gob atmosphere, detection of explosion hazards and their assessment is reactive. When a detected methane concentration exceeds regulatory thresholds response plans are followed to avoid a catastrophic event. Yet, in many cases, including the Sago Mine explosion in 2006 (12 fatalities), the Upper Big Branch explosion in 2010 (29 fatalities), the Pike River Mine Explosion in 2010 (29 fatalities) and the Turkish Soma Mine disaster in 2014 (301 fatalities) early detection was unsuccessful and did not prevent an explosion.

Transition from bleeder ventilated panels, the current regulatory standard in the US, to U-Type progressively sealed panels is the most effective method of reducing the spontaneous combustion risk. Nitrogen injection in addition to progressive sealing may mitigate, but not eliminate, methane and spontaneous combustion hazards. This strategy has been used in the mining industry since the 1980’s
(Both, 1981 and Harris, 1981) although it is only practiced by two mines in the US. Numerical modeling has investigated injection location, number of injection points and injection flow rates as well as panel configuration. Nitrogen has been shown to reduce oxygen concentration in the gob to mitigate the risk of a spontaneous combustion event from occurring. More recent research focused on explosive potential and concluded that nitrogen was also effective at mitigating this hazard. Despite the use of nitrogen, progressively sealed panels have a region directly in the face on the tailgate side remains methane rich, deficient in oxygen and in some cases within the explosive range. This region is adjacent to working areas and poses a significant safety concern in the event of an ignition. The investigation of the Upper Big Branch catastrophe concluded that the ignition initiated near the tailgate (McAteer et al., 2011).

The back return system is a modification of the U-Type ventilation scheme in which all or a portion of the air is forced to return one crosscut in the face. This method has been effective in eliminating the methane rich region immediately inby the tailgate shields (Diamond et al., 1994). One concern with the back return is the increased maintenance demands and the increased oxygen ingress that could initiate a spontaneous combustion event. Nitrogen injection research involving a back return style gob is sparse and findings from U-Type ventilation schemes may not apply to back return schemes.

1.2 Research objectives

Parametric studies can determine gob gas compositions for a variety of operating conditions. The porous media distribution of the gob requires a geo-mechanical assessment of the longwall mining process. CFD programs are well suited for modeling the porous media flow and turbulence is required to sufficiently assess gob hazards. CFD is also capable of predicting the gob atmosphere and versatile enough to assess hazards to determine the best mitigation strategies. Further, the transient response of ventilation changes can be analyzed.

The purpose of this dissertation is to expand on previous research regarding progressively sealed longwall panels with a U-Type ventilation scheme. Grubb concluded that progressively sealed longwall panels were a feasible and economically justifiable method of reducing the risk of spontaneous combustion (Grubb, 2008). Worrall (2012) concluded that nitrogen injection was effective at reducing the volume of explosive gas inside the gob. Worrall’s findings also showed that for U-Type ventilation schemes a volume of explosive gas exists immediately inby the shields adjacent to the tailgate. This zone
remained present over a large range of nitrogen injection quantities, up to 0.8m$^3$/s, and longwall face ventilation quantities ranging from 19 to 42m$^3$/s. Future research recommendations in both dissertations included removal of the explosive gas zone adjacent to the face in this region.

The goal of this research is to demonstrate the effectiveness of a back return at eliminating the explosive gas zone directly inby the face. Nitrogen injection will be used to offset the additional oxygen ingress resulting from the implementation of a back return. Geo-mechanical modeling will be used to create porous media distributions to describe the gob. These geo-mechanical models will be validated using subsidence and shield loading data provided from two industry partners. The porous media distributions will be implemented into the CFD models to study gob gas distributions. The intent of the CFD research is to control both the volume and location of the explosive gas in addition to decreasing the prevalence spontaneous combustion hazards. This task will be accomplished though investigation of various face ventilation and nitrogen injection schemes. Successful completion of this task would determine a combination of ventilation parameters that result in a safer work environment for underground coal miners.

The hypothesis is that progressive nitrogen injection in conjunction with a back return scheme creates a safer work environment than a traditional U-Type ventilation scheme in terms of both explosive gas and spontaneous combustion hazards.

1.3 Thesis organization

This dissertation is composed of six chapters. The chapters are organized in a manner that addresses the scientific approach used to complete this research.

Chapter one introduces the issue and its significance to industry. The research objectives are stated and the general organization of this dissertation is presented.

Chapter two contains the literature survey and introduces the readers to the methane and spontaneous combustion hazards associated with longwall coal mining. A description of current monitoring technology is briefly discussed followed by an introduction to the various methods of longwall ventilation. This is followed by the geo-mechanical aspects of longwall mining. Discussion includes the caving behavior and gob formation along with important laboratory tests used to describe the mechanical properties of the gob. The numerical modeling software $\text{FLAC}^{3D}$ is introduced and
previous research using advanced numerical models to study the gob is summarized. Also included is a discussion of the methodologies used by other researchers to describe the porous media properties of the gob. Following is a historical summary of the past and present research completed on gob gas distributions. A discussion regarding areas of improvement in the previous geo-mechanical and gob gas distribution research is also included. This chapter concludes with a statement regarding the expected impact this research will have on the longwall coal mining industry.

Chapter three introduces the numerical modeling required for the geo-mechanical portion of the research. The background information relating to the two partner mines is presented. The fundamental concepts for the software package, FLAC$^3$D, including the constitutive models used to describe the rock mass and gob is presented. The sensitivity and calibration of the mechanical properties assigned to each model is also included. This continues with the formulation and validation of the geo-mechanical model, including a justification for the need to use stepped extraction to accurately model the dynamic behavior of an active longwall face. The methodology used to formulate the porous media distribution and the resulting distributions are given. This chapter concludes with a summary of the findings from the geo-mechanical modeling portion of the research.

Chapter four gives an overview of the field of computational fluid dynamics. Included are the constitutive conservation equations and the governing equations describing the k-ε turbulence model. Next is a brief discussion of the methodology used by Fluent, the program used for this portion of the research, to describe porous media behavior of the gob. The finite-volume discretization method used by most CFD software is described along with meshing of the computational domain and the iterative process used to solve the equations. Next the solver settings used inside of Fluent are described and the post processing algorithms used to analyze the results are introduced. This chapter concludes with a description of the model and the model validation process.

Chapter five is an overview of the results and a brief economic justification of nitrogen injection. It begins with a comparison of the flow patterns inside of a U-Type ventilation scheme and a back return scheme. The hazards in each scheme are discussed. Next, the concept of a dynamic seal defined as the nitrogen rich region in the interior of the gob that advances with the face. Discussion of the dynamic seal follows. This is followed by a transient study of a panel sealing study which investigates the impact of methane emission quantities and nitrogen injection. The economic justification of the use of nitrogen is presented in the next section. Nitrogen injection costs were provided by one of the partner mines and applied to the model. This chapter details the important assumptions and costs and compares the
nitrogen injection rates discussed in the results. This chapter concludes with a summary and recommendations drawn from the research.

Chapter 6 discusses the conclusions and important findings drawn from this research. A statement of the novel contribution to the field of mining engineering is included. This chapter concludes with recommendations for future work.
CHAPTER 2
LITERATURE SURVEY

There is a significant amount of previous research regarding both geo-mechanical and gas flow modeling of longwall panels. There is still room for improvement and advancing the current understanding in both of these fields. In particular, the geo-mechanical research regarding active panels has been limited to gate road pillar stability, longwall face studies and dynamic surface subsidence. Geo-mechanical models require an understanding of the caving behavior and gob compaction mechanisms. Gob compaction is directly related to surface subsidence; therefore research regarding dynamic subsidence is relevant for simulation of an active longwall panel. Previous research regarding the application of numerical programs to both the geo-mechanical and gas flow work is crucial background information.

Longwall mining is a highly productive underground coal mining technique. Development is completed by driving entries, gateroads, set-up rooms and recovery rooms with continuous miners. The longwall begins in the start-up room and advances towards the recovery room, the face advances after a complete face pass across the full width has been completed. The panels are roughly 300m to 500m wide by several thousand meters long. As the face advances the shields move forward and the previously supported roof is allowed to cave forming the gob. Methane and spontaneous combustion are the two ventilation hazards most commonly associated with the gob. The risks associated with these hazards depends on the gob gas distribution, which is directly related to the reservoir properties of the gob.

2.1 Methane and spontaneous combustion

Methane and other hydrocarbon gases are commonly encountered during longwall coal mining operations. Longwall coal mining is a caving method that causes subsidence to the overlying rock strata. The caved gob and damaged upper coal beds can liberate methane. When mixed with ventilation air, methane presents an explosion hazard. The ventilation system supplies fresh air to the face and some leakage occurs into the caved gob through gaps in the shields. This mixing of air and methane presents a safety concern in the form of hazardous and potentially explosive gas mixtures. Coal mine ventilation regulations provide a safety buffer requiring steps be taken at certain methane thresholds including
evacuation of the workplace when the methane exceeds 1.0% in accordance with 30 CFR §75.323. The industry standard for detecting methane includes hand held and machine mounted methane detectors that serve as continuous but static measurement points and only provide readings in active areas. The effectiveness of these detectors depends on three factors according to Kissell (2006):

- Placement of the sensing head
- Sensor response time
- Cleanliness of the sensing head

Machine mounted detectors are located on the continuous miner and longwall shearer. Handheld methane detectors used during pre-shift and on-shift examinations give a reading but only at the time of measurement. Atmospheric monitoring systems (AMS) relay air quality measurements, taken from fixed locations throughout the mine, back to the surface. The AMS also displays the gas concentrations on the panel itself and sounds an alarm when a threshold is exceeded. Some mines use tube-bundle systems that allow continuous atmospheric monitoring mine-wide. The tube bundle system provides the mine with gas concentration readings in sealed or otherwise inaccessible areas of the mine. Both AMS and tube bundle systems allow the mine to observe trends in changing gas concentrations. One issue with present methane detection systems is in regards to location of the sensor with respect to the gas emission source, see Figure 2.1. If the sensor is located at a distance where sufficient dilution has occurred to bring the methane concentration below the 1% threshold the hazard may go unnoticed. Further, mines only measure gas concentrations in active working areas and around the fringes of the gob. The gas composition inside the gob is unknown, as shown in Figure 2.2. The gob presents several hazards including methane explosion and spontaneous combustion. As ventilation air containing approximately 21% oxygen mixes with the gas emission source, approximately 100% methane, from surrounding strata there must exist fringe zones of explosive gas. The location and extent of these explosive zones cannot be determined from current monitoring systems and may even go entirely undetected by the system. An understanding of gas distributions in the gob is required for proper risk management to enhance mine safety.

Spontaneous combustion of coal, referred to as spon com, from excessive oxygen penetration in the gob is another major safety concern in mines whose coal has a propensity to self-combust. A number of heating events have occurred in recent history leading to major production or equipment
losses and in some cases loss of life. A list of recent, significant spontaneous combustion events are listed in Table 2.1.

Figure 2.1: Depiction of methane dilution from ventilation air (Kissell, 2006)

Figure 2.2: Hypothetical zones of potentially explosive gas mixtures in a longwall gob. The orange rectangle is the perimeter of the gob and the extent that present monitoring systems could detect. The yellow fill corresponds to an unknown gas mixture that could be explosive or contain oxygen content sufficient to promote and sustain spontaneous combustion reactions. Modified from Zipf, Sapko and Brune (2007)
Table 2.1: Significant Spontaneous Combustion Events (Grubb, 2008)

<table>
<thead>
<tr>
<th>Year</th>
<th>Mine</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>Box Flats (Australia)</td>
<td>18 Fatalities</td>
</tr>
<tr>
<td>1975</td>
<td>Kianga (Australia)</td>
<td>13 Fatalities</td>
</tr>
<tr>
<td>1991</td>
<td>Ulan (Australia)</td>
<td>Loss of US$60 million</td>
</tr>
<tr>
<td>1994</td>
<td>Moura No. 2 (Australia)</td>
<td>11 Fatalities</td>
</tr>
<tr>
<td>1997</td>
<td>Galatia (U.S.A.)</td>
<td>Loss of US$38 million</td>
</tr>
<tr>
<td>1997 - 1998</td>
<td>North Goonyella (Australia)</td>
<td>Loss of Longwall</td>
</tr>
<tr>
<td>1999</td>
<td>Sanborn Creek (U.S.A.)</td>
<td>Mine Idled 9 months</td>
</tr>
<tr>
<td>2000</td>
<td>West Elk (U.S.A.)</td>
<td>Loss of US$50 million</td>
</tr>
<tr>
<td>2003</td>
<td>Southland (Australia)</td>
<td>Loss of Longwall – Mine Closed / Sold</td>
</tr>
<tr>
<td>2006</td>
<td>Dartbrook (Australia)</td>
<td>Mine Closed</td>
</tr>
</tbody>
</table>

Many of the coals mined in the Western US, as well as other parts of the world, are prone to spontaneous combustion. The combination of spon com and high methane emission rates creates a hazardous situation. Oxygen ingress into the gob must be closely monitored and controlled in these mines to prevent a combustion event in the gob, particularly during a face stoppage or a period of slow face advance. During these events the gob is often subjected to air flow rates incapable of dissipating heat, known as critical velocity air flow, for an extended period of time. This condition increases the risk of spon com (Mitchell, 1972; Feng, Chakravorty and Cochrane, 1973; Banerjee, 1985; Funkemeyer and Kock, 1989; Cliff, Rowlands and Sleeman, 1996; Kaymakci and Didari, 2002). For most coals the spon com reactions cease below 6% oxygen but for other coals this threshold is as low as 2% oxygen (Highton, 1979). Spon com indicator gases including carbon monoxide, hydrogen, ethylene and other hydrocarbons can be detected by present technology but only after the gas reaches the sensor in sufficient concentration to exceed the alarm threshold.

The exact mechanisms and controlling factors of spon com are not fully understood. There have been numerous attempts to understand the impacting factors and to classify the risk of spon com. Spon com is an exothermic reaction between coal and oxygen that begins at ambient temperature (Smith, Miron and Lazzara, 1991). If there a sufficient supply of oxygen and there is no heat dissipation the coal can proceed to thermal run away and eventually a fire (Banerjee, 1985; Cliff and Bofinger, 1998). The first attempts identified the reactivity of the coal as the primary factor influencing spon com propensity (Graham, 1920; Cliff and Bofinger, 1998). Researchers have since identified additional intrinsic and
extrinsic factors influencing the propensity for spon com. Other research includes tests for measuring the spon com propensity of a certain coal (Beamish, 2008; Beamish and Beamish, 2010; Beamish and Beamish, 2011; Beamish and Beamish, 2012).

A typical measure of spon com propensity is shown in Figure 2.3, the propensity is measured as a temperature rise over an interval of time, usually expressed in °C per hour.

![Figure 2.3: A typical measure to determine spon com propensity of different coals showing the temperature rise over time for several types of coal subjected to a moist adiabatic laboratory test (Beamish and Beamish, 2012)](image)

Major intrinsic properties that influence spon com propensity include coal rank, maceral content, moisture content and pyrite content. The propensity tends to increase with lower ranked coals, for instance anthracite is not prone to spon com events (Banerjee, 1985; Beamish, 2005). Although the exact mechanism is not understood, maceral content has been shown to affect spon com propensity (Chamberlain and Hall, 1973; Cliff and Bofinger, 1998). Coal seams are often formed of banded zones of macerals with each zone containing different intrinsic properties. The physical interfaces between maceral groups are believed to initiate the process during the early stages of spon com by creating and retaining heat. Researchers have found that the moisture content of the coal can serve as both an
initiator and a deterrent for spon com (Berry and Goscinski, 1983; Arisoy and Akgun, 1994; Mitchell, 1996; Akgun and Essenhigh, 2001; Bell et al., 2001; Blazek, 2001). As the moisture evaporates, the evaporation cools the surface temperature of the coal and can delay or even stop the spon com process. When the process of wetting is followed by evaporation, the coal pores are swelled and then cleared. With the pores cleared, a larger surface area is exposed for the coal to react with the oxygen and advance the process of spon com. The presence of pyrite has been shown to be both a promoter and an inhibiter of the process. Pyrite has been found to accelerate the spon com reaction once pyrite oxidation begins (Beamish, 2005). However, coals with low pyrite content have been shown to have a high propensity for spon com, since high levels of pyrite content are understood to be a heat sink that delays the thermal run away process (Beamish and Blazak, 2005). In addition some pyrites such as borates and salts of calcium and sodium were shown to inhibit the development of spon com (Chamberlain and Hall, 1973).

The development of spon com is studied in adiabatic ovens to capture the temperature rise in degrees over a given interval of time, as shown in Figure 2.3. Research has shown that spon com accelerates with temperature and eventually reaches a point of thermal run-away, at which point the test is stopped for safety reasons. Four distinct stages of spon com development have been identified and individually associated with a distinct temperature range (Cygankiewicz 2000). The first stage occurs until the coal reaches 70°C, this stage is associated with oxygen absorption on the coal’s surface. The second stage occurs from 70-150°C and is associated with a benzene smell characteristic of spon com events. This stage involves the decomposition of the coal and the release of CO, CO2, H2O and other heavier hydrocarbons. Further oxygen absorption and accelerated heat generation occur between 150-230°C, in the third stage. The final stage of spon com is the point at which the coal experiences thermal run away and combustion if the process is not stopped. This stage occurs between 230-300°C, depending on the coal. Once an event has reached thermal run away it can become an ignition source for explosive methane accumulations.

2.2 Mine safety technologies

Mine safety technologies can be categorized into active and passive mitigation technologies. Active mitigation technologies include degasification boreholes, gob vent boreholes, nitrogen injection, Tomlinson Boilers, pressure balances seals and jet engines converted to produce inert exhaust gases. Passive mitigation technologies include tube bundle systems, bag gas samples and atmospheric
monitoring devices. Active mitigation technologies can either be used to reduce the risk of an event occurring or after an event has occurred. A complete review of mine safety technology to mitigate safety and operation risks was completed by Grubb (2008) who also determined the efficiency and cost effectiveness of each option. Final conclusions recommended the use of a tube bundle system, gob ventilation boreholes, progressive sealing and inertization of longwall panels for mines with a moderate to high propensity for spontaneous combustion.

2.2.1 Methane degasification systems

Degasification boreholes are drilled into the coal seam prior to mining to reduce the amount of methane released when mining the coal seam. They can be drilled vertically from the surface or horizontally into the seam from development entries, as shown in Figure 2.4. The method used to drill the horizontal in-situ degasification holes and the orientation of the holes can impact the effectiveness of this strategy (Karacan, Diamond and Schatzel, 2007b). During the study it was concluded the wells should be drilled at least 6 months prior to mining and maximum benefits were realized if the wells were left in place for a 12 month duration.

Gob vent boreholes, or GVBs as shown in Figure 2.4, capture gas emissions from the fractured zone before the methane can migrate towards the active workings. The GVBs are drilled prior to mining and activated by installing a vacuum pump once the face has advanced to within a sufficient distance of the GVB. The GVBs are typically drilled within a short distance of the mined seam. The entire borehole is cased to improve structural durability. The bottom portion of the casing is slotted to allow degasification. Once the face has reached the GVB, gas production begins and is sustained for several weeks or months. Initial gas production is high and rich in methane with concentrations of 80-100%. Over time, gas production begins to decrease and eventually the vacuum pumps are shut off and the GVB is allowed to vent at atmospheric pressure. A model by Karacan (2009a) to study parameters inclusive of drilling, completion, location and vacuum pressure was developed to evaluate the effect of GVB performance. A sensitivity analysis was completed to study the impact on total gas flow and methane concentration produced by the GVBs as shown in Figure 2.5. Typically, mines employ a combination of active degasification methods to control methane emission during active mining.
Figure 2.4: Methane degasification systems typically used in mines (Karacan, 2009a)
Figure 2.5: Sensitivity analysis for total gas flow (A) and methane concentration (B) produced from GVBs (Karacan, 2009a)
2.2.2 Nitrogen injection

Several western US coal mines are prone to spontaneous combustion events and underground fires. Bessinger et al. (2005) listed several examples of recent fire events caused by spontaneous combustion including RAG’s Willow Creek Mine in 1998 and 2000, Arch Coal’s West Elk Mine in 2000, Arch’s Skyline Mine in 2002, Andalex Resource’s West Ridge Mine in 2003 and Signal Peak Energy’s Bull Mountain No 1 Mine in 2011. Fighting underground coal fires is a very complex and difficult task. Some fires are fought underground by mine rescue teams under apparatus. Other underground mine fires are fought remotely from the surface due to safety concerns. Foam or inert gases (N$_2$ or CO$_2$) are injected through surface boreholes to suffocate the fire. In Australia a common fire-fighting technique is the use of Tomlinson Boilers or modified jet engines. Each device is similar in principle, consuming fuel to release the inert products of a combustion reaction although the jet engine produces significantly higher quantities of inert gas. The best practice is to mitigate the risk of spontaneous combustion before it occurs. Nitrogen injection can be used for this purpose by diluting oxygen levels in the gob.

Nitrogen injection may also be used to dilute gob gas emissions. The potentially explosive atmosphere that exists in the gob can be minimized (Marts et al., 2013) and oxygen ingress can be diluted (Gilmore et al., 2013) using nitrogen injection. Nitrogen is usually produced by either an air separation unit, ASU, which can produce nitrogen with a quality exceeding 99.9%, or more commonly by nitrogen membrane plants. Only in rare cases is it feasible to use an ASU due to economies of scale. Membrane plants are more scalable but the quality is lower and is a function of gas output. Mine E reported their membrane plant can produce 0.7 m$^3$/s at 95% N$_2$, 0.5 m$^3$/s at 98% N$_2$ and 0.35 m$^3$/s at 99% N$_2$ (Mine E, 2013). A typical nitrogen membrane production plant is shown in Figure 2.6. The nitrogen, produced on the surface, is pumped underground through pipe networks. The nitrogen is delivered underground to the gob through cross cut seals and the injection location is advanced with the longwall. Common practice is to inject the nitrogen immediately inby the last open cross cut in the near vicinity of the active face. The purpose of nitrogen injection is to limit the area exposed to explosive volumes of gas. Normally, without nitrogen injection, there is a fringe region between fresh air and fuel-rich methane concentration that is explosive. As methane mixes with and displaces the face ventilation air, there is a period of time during which the volume of gas becomes and remains explosive until the mixture becomes fuel rich and is no longer explosive. Nitrogen injection can be used with the intent of ‘skirting’ this explosive area or reducing the amount of time in the explosive range thus increasing mine safety, see Figure 2.7.
Figure 2.6: Typical Membrane Nitrogen Production Plant (Bessinger et al., 2005)

Figure 2.7: Nitrogen Injection to mitigate explosive gas mixtures (Grubb, 2008)
Table 2.2: Gas monitoring response plan from Mine E

<table>
<thead>
<tr>
<th>Location</th>
<th>Monitor</th>
<th>Alert</th>
<th>Alarm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tailgate Measuring Point Inby (Gob Side Cross Stopping)</td>
<td>Methane</td>
<td>0.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Tailgate Measuring Point Inby (Gob Side Cross Stopping)</td>
<td>Carbon Monoxide</td>
<td>100 ppm</td>
<td>125 ppm</td>
</tr>
<tr>
<td>Tailgate Measuring Point Outby Mix Point Regulator</td>
<td>Methane</td>
<td>0.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Tailgate Measuring Point Outby Mix Point Regulator</td>
<td>Oxygen</td>
<td>19.7%</td>
<td>19.5%</td>
</tr>
<tr>
<td>Tailgate Measuring Point Outby Mix Point Regulator</td>
<td>Carbon Monoxide</td>
<td>15 ppm</td>
<td>25 ppm</td>
</tr>
<tr>
<td>Sample Points Headgate Shield 1 Mid Face Shield and Last Shield on Longwall Face</td>
<td>Methane</td>
<td>0.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Sample Points Headgate Shield 1 Mid Face Shield and Last Shield on Longwall Face</td>
<td>Carbon Monoxide</td>
<td>15 ppm</td>
<td>20 ppm</td>
</tr>
<tr>
<td>Sample Points Headgate Shield 1 Mid Face Shield and Last Shield on Longwall Face</td>
<td>Oxygen</td>
<td>19.7%</td>
<td>19.5%</td>
</tr>
<tr>
<td>Longwall Return Atmosphere Outby the Tailgate</td>
<td>Carbon Dioxide</td>
<td>0.5%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

2.2.3 Mine atmospheric monitoring systems

Real time monitoring is a passive measure that is done to some degree at every mine. Technologies include hand held devices, fixed point devices, bag sample testing, and tube bundle monitoring systems. Hand held devices can detect nitrogen, oxygen, methane, carbon dioxide, carbon monoxide, hydrogen, NO\textsubscript{x} species, hydrogen sulfide, and sulfur dioxide. Fixed point devices are used to measure common gases such as oxygen, methane, and carbon monoxide. Fixed point devices and handheld devices are set to sound an alarm once the gas reading exceeds a predetermined threshold. An example of gas threshold limits for Mine E is given in Table 2.2. Bag gas samples are taken at selected points in the mine to give a complete analysis. The bag samples are then run through a gas chromatograph and can be tested for a variety of gas species. Tube bundle systems give a continuous stream of gas that can be analyzed within minutes. The tubes can be placed anywhere in the mine, including areas not accessible with electronic AMS sensors. The gas must travel through thousands of feet of tubing from its monitoring point to the reading station. Therefore results can be delayed by up to 30 minutes.
2.3 Geomechanical aspects of longwall mining

The geo-mechanical aspects of longwall mining must include a discussion regarding the caving behavior of the overburden, the mechanisms of gob compaction, numerical modeling of geomechanical aspects of longwall mining, dynamic subsidence and historical research regarding permeability and porosity distributions of the gob.

2.3.1 Caving behavior and gob compaction

During an active longwall mining operation the coal is continuously extracted and the shield supports are advanced. As the shields advance, the immediate roof is allowed to collapse into the void, leaving a pile of rock fragments referred to as the gob. The caving of the roof continues upwards until the gob comes into contact with the overlying fractured zone. Initially, the gob is loosely compacted with a high void ratio and high permeability. As the face continues to advance, the gob takes additional loading and compacts further. The strata overlying the gob is also disturbed by the passing longwall face. The severity of the disturbance is greatest in the immediate roof and decreases near the surface. There are three zones of disturbance that can be identified in the strata above an excavated longwall panel (Peng and Chiang, 1984; Singh and Kendorski, 1981). These are the gob, the fractured zone and the bending zone as shown in Figure 2.8.

The extent of each zone is dependent on geological conditions, type of overburden strata and the excavation height. The vertical extent of the gob depends on the strength of the immediate overburden and the bulking factor of the gob material. The vertical extent of the caved zone can be 3 to 6 times the extraction thickness (Esterhuizen and Karacan, 2005). The fractured zone surrounds the caved zone and can be characterized with near vertical fractures, bedding plane shearing and bedding plane separation. The vertical extent of the fractured zone can be 30 to 60 times the extraction thickness (Esterhuizen and Karacan, 2005). The shape of the fractured zone can vary between arch-shaped and saddle-shaped profiles, depending on overburden properties and excavation width (Bai, Kendorski and Van Roosendaal, 1995). The extent of deformation in the fractured zone reaches a maximum near the center of the panel and decreases near the gateroads as the pillars take more of the load. The bending zone lies above the fractured zone and extends mostly to the surface. The rock in this zone behaves as a continuous medium and is nearly un-fractured; as the layers are deflected over the
extracted edges of the longwall panel shearing occurs along bedding planes (Hasenfus, Johnson and Su, 1988).

Figure 2.8: Depiction of vertical cross section showing zones of disturbance above a longwall panel (Esterhuizen and Karacan, 2005)

The compaction of the gob is not fully understood. It does depend on the initial bulking factor of the gob and the strength of the rock fragments. The initial bulking factor depends on the shape of the fragments, the fall height of the fragments and size distribution of the fragments (Esterhuizen and Karacan, 2007; Yavuz, 2004). When the cave is first initiated, the fall height is often greater than the dimensions of the rock fragments and they drop to the floor in an unorganized fashion, producing a large bulking factor. A caving model developed by Esterhuizen and Karacan (2007) postulated that the bulking factor decreases to zero in the upper portions of the gob due to the fall distance. The gob compaction was modeled by assuming the bulking factor reduction was directly proportional to the amount of gob compaction, in a one to one (1:1) ratio. The initial void ratio of the gob material is between 30 and 45% from laboratory tests by Pappas and Mark (1993). The majority of the gob compaction occurs shortly after the face advances a sufficient distance for the gob to begin to take load from the overlying strata. As the face continues to advance and the compaction continues, the gob
material stiffens and exhibits a strain hardening behavior. Nearly all compaction of the gob is plastic and irreversible. The first estimate of the gob material’s response to loading was presented as a hyperbolic relationship determined by Salamon (1990) given in Equation 2.1.

\[ \sigma = \frac{a \epsilon}{b - \epsilon} \]  

(2.1)

In Equation (2.1) \( a \) and \( b \) are empirical parameters and \( \epsilon \) is the amount of plastic volumetric strain. The parameter \( a \) is the stress when the strain is equal to \( b/2 \), and represents the amount of compaction that occurs before the gob begins to harden. The parameter \( b \) is related to the bulking factor and represents the initial void ratio of the gob material. The value can range between 40 – 50%, depending on lithology in the immediate roof which caves to form the gob. The maximum amount of gob compaction is defined by the value of \( b \). The strain hardening behavior of the gob material was documented for coal measure shale and sandstone fragments representing a caved gob (Pappas and Mark, 1993). During the testing by Pappas and Mark it was noted that stronger sandstone had a stiffer response than weaker shale. The results of their tests are given in Figure 2.9. Estimates for the strain hardening curves have been given by previous researchers for a variety of rock types and coal mining regions (Pappas and Mark, 1993; Yavuz, 2004; Esterhuizen, Mark and Murphy, 2010). The strength of the gob material, or the \( a \) parameter, depends on rock fragment strength, however, it is not well understood how the strengths of the fragmented rocks relate to the in-situ intact rock strength. This parameter is varied during calibration to match abutment stresses and subsidence profiles measured in the field.

![Stress Strain behavior of gob material response test (Pappas and Mark, 1993)](image-url)
2.3.2 Use of FLAC$^{3D}$ to model longwall caving

Numerical models are useful for determining gob compaction over an entire longwall panel. Several researchers have chosen FLAC3D (Badr, 2004; Yavuz, 2004; Esterhuizen, Mark and Murphy, 2010). FLAC3D contains a Double Yield model capable of simulating materials that experience significant and irreversible compaction. The Double Yield model is recommended for hydraulically placed backfill or lightly cemented granular materials, similar to gob material. FLAC$^{3D}$'s implementation of the double yield model allows the user to assign the strain hardening behavior of the gob to the appropriate elements in the numerical model. The double yield model includes a volumetric yield surface, in addition to shear and tensile failure envelopes, to account for permanent volume changes caused by isotropic pressure loading. The material “hardens” or resists further deformation by means of a user defined “cap pressure” table. This table consists of a series of points along a stress strain curve, similar to the strain hardening curve developed from laboratory tests of gob material (Pappas and Mark, 1993). The hardening behavior is activated by volumetric strain and the program uses the table values to determine the volumetric strain that should be applied to the element based upon the stress calculated. The tangential bulk and shear moduli are updated by the program as the material deforms to increase stiffness. The material properties selected for the gob vary greatly between researchers. This variation is a result of the in-situ properties of the gob being site specific and difficult to measure. Additional built-in constitutive models to simulate actual behavior of rock mass include the strain softening and Ubiquitous joint models. The Ubiquitous joint model is a plastic model that simulates the anisotropic strength of rock mass by including ubiquitous planes of weakness within a Mohr Coulomb solid matrix. The Ubiquitous joint model is important for simulating the anisotropic failure of the overburden and impacts the loading of the gob. The strain-softening model simulates nonlinear softening behavior according to user-defined relationships for Mohr Coulomb properties as a function of plastic shear strain. Numerical models were calibrated against surface subsidence measurements, stress abutment measurements and checked for super-critical behavior sensitivity.

A panel becomes super-critical when the full overburden weight rests on the gob. This point is defined by the abutment angle. In Appalachian coal seams the panel becomes supercritical when the width exceeds approximately 1.2 times the panel depth (Peng, Ma and Zhong, 1992). At this point the subsidence profile flattens and remains constant until the gate road pillars begin to relieve some of the load of the overburden. This flattening behavior can be explained by the excavation width exceeding the area of influence from the abutment support provided by the gateroads. Flattening occurs when the
distance from the gate roads is large enough that the full weight of the overburden rests on the gob material.

One important topic has yet to be addressed by previous researchers, dynamic gob compaction. The compaction of the gob is dependent on the distance from the point of interest to the active face and time elapsed since the coal was mined. The compaction is a dynamic process and directly related to surface subsidence. Watchel (2012) along with Esterhuizen and Karacan, (2005) used FLAC3D to extract the coal in a single step, leading to a subsidence basin that is symmetric along both the length and width axis. A subsidence study by Campoli et al., (1993) concluded that the subsidence profile is not symmetric from the start-up room to the current face location, as seen in Figure 2.10. The study used vibrating stress meters to correlate stress with surface subsidence for a sub-critical panel near Benton, IL.

![Subsidence Profile](image)

**Figure 2.10:** Generalized subsidence along the longwall panel centerline (Campoli et al., 1993)

Previous attempts to model the dynamic movement of a longwall panel involved extracting the coal incrementally and analyzing the dynamic stresses and strata displacements. Modeling showed that
it was important to run the model to equilibrium after each extraction step. Modeling efforts discussed below allowed the models to step to equilibrium after each extraction step.

A two dimensional (2-D) stepped extraction model (Esterhuizen and Karacan, 2005) was used to evaluate methane emission rates from a passing face. The results for fractured zone permeability were input into a reservoir model. The 2-D study could not determine effects near the edges of the panel, particularly near the tailgate where the risk of explosive potential is greatest (Worrall, 2012). A similar approach by Wachel (2012), in a full three dimensional (3-D) model, extracted the coal in 33 ft. (10 m) increments. This model was also used to determine the 3-D porosity and permeability distributions in the gob. A potential issue with this model was that the overburden was modeled assuming elastic Mohr Coulomb behavior and therefore the response could not predict the caving process with enough accuracy. The overburden should be modeled using FLAC’s built in Ubiquitous joint model to simulate anisotropic gob loading. The Ubiquitous joint model accounts for jointed rock mass by inserting a failure plane wherever the model predicts that the user defined strength of a joint is exceeded. As a result of the Mohr Coulomb simplification, the panel did not achieve a flat subsidence profile, characteristic of supercritical behavior, over either the width or length of the panel. This suggests that modeling the overburden with Ubiquitous joint behavior and refining the properties assigned to the gob is required.

2.3.3 Dynamic subsidence

Dynamic gob compaction research does not exist, although there is a direct relationship between gob compaction and subsidence. Therefore, the topic of dynamic subsidence prediction which has been researched previously is relevant. The work by Campoli et al., (2003) studied a panel in the Pocahontas #3 Seam and is shown in Figure 2.10. Subsidence monitoring and load cells, located in the gob, were used in a study by Oyanguren (1972) to measure longwall gob loading for a Potash mine in Spain. There was sufficient correlation between the increase in vertical stress on the gob and surface subsidence. Oyanguren concluded that at a distance of roughly 0.9H (90% overburden cover height) behind the face, the pressure on the gob had returned to virgin, in-situ pressure and the full subsidence had been reached. He also determined that this was not sensitive to changes in overburden thickness, ranging from 180 – 365m. A study by the Bureau of Mines (Janes, 1983) at an Illinois coal mine found that the gob loading returned to virgin in-situ pressure at a distance of roughly 0.3H behind the face and the gob stabilized at a distance of 0.75H. Wilson found the cover pressure should be reached at a distance of 0.3H for seam thicknesses up to 3m (Wilson, 1982).
Jeran and Trevits (1995) completed a dynamic subsidence study for a sub-critical Pittsburgh coal longwall panel. The purpose of this study was to determine the effect of location on time to reach final subsidence or subsidence rate. They concluded that subsidence reached 90% of its final value at a distance of roughly 1.0H from the face in the center of the panel. However, for this same point, the subsidence adjacent to the gateroads was only 60% of its final value. Three other panels (two sub-critical and one supercritical) were investigated during the study and had the same percentage of final subsidence along the panel centerline. The monuments adjacent to the gateroads only achieved 40–70% of the final subsidence value at this same point. Neither the panel width nor the lithology affected the duration to reach final centerline subsidence. The mine with more abundant and thicker sandstone units lagged most, only achieving 40% of final subsidence at a monument adjacent to the gateroads. The researchers believed that the stiffer sandstone units cantilever farther out over the gob and take additional time to break and load the gob. Observations and experiences in Chinese and European coal mines (Cui, Wang and Liu, 2001) show the subsidence reaches a maximum value once it has advanced approximately 1.2 – 1.4H from the start-up room. Further subsidence reaches the surface once the face has advanced 0.25 – 0.5H from the start-up room.

A summary of the research discussed above concludes dynamic subsidence rates are quicker near the center of the panel and slower near the gateroads. The rates near the center of the panel are not sensitive to panel width, depth of cover or strata types. The rates near the gateroads are dependent on overburden lithology.

Dynamic subsidence can also be determined empirically through the Knothe time function (Knothe, 1957). Since its development it has been modified (Peng, Ma and Zhong, 1992; Cui, Wang and Liu, 2001) to account for factors such as radius of influence and face advance rate. The fundamental form of the Knothe time function is a simple differential equation given below in Equation (2.2. Solving the differential equation gives Equation (2.3.

\[
\frac{dW(t)}{dt} = c_{Knothe}(W_o - W(t))
\]  

\[
W(t) = W_o(1 - e^{-c_{Knothe}t})
\]  

(2.2)  

(2.3)
In the equations above \( W(t) \) is the subsidence at time \( t \), \( t \) is the time, \( W_0 \) is the final subsidence at a given point and \( c_{\text{Knothe}} \) is a proportionality factor related to the physical and mechanical properties of the overburdened rock mass. Some researchers have suggested that extraction rate, or speed of advance of the longwall, may have some impact on dynamic subsidence. Experience from four Chinese, two Polish and one German mine suggests that \( c \) decreases for slower extraction rates and greater mining depth (Cui, Wang and Liu, 2001). The sample size studied did not allow for the two variables to be separated. A study in New South Wales (Holla, 1998) concluded that subsidence development curves (dynamic subsidence) varied significantly with extraction rate. Faster advance rate was shown to cause a subsidence to reach a final value quicker. Variables to account for radius of influence and face advance rate were included in another prediction of dynamic subsidence (Peng, Ma and Zhong, 1992), given in Equation (2.4 where \( c_{\text{Peng}} \) is the time coefficient (1/yr.), \( r \) is the radius of major influence and \( V_p \) is the face advance rate in m/yr.

\[
K_{\text{Dyn}} = K_{\text{Final}} \left( 1 - e^{- \frac{c_{\text{Peng}} r}{V_p}} \right) \tag{2.4}
\]

Other researchers did not find face advance rate to have a significant effect on dynamic subsidence. Studies on Appalachian coal fields (Jarosz, Karmis and Sroka, 1990; Adamek, Jeran and Trevits, 1992; Jeran and Trevits, 1995) could not find conclusive evidence suggesting face advance rates had an effect on dynamic subsidence. Instead they determined the rate of subsidence was more dependent on the distance from the active face.

Despite the disagreement between researchers who claim subsidence rate is dependent on face advance rate and those who claim subsidence rate is dependent on distance from the active face both variables are closely related. A faster face advance rate implies the distance from the active face increases quicker than for a slower longwall, and therefore the virgin stresses in the gob are restored quicker. None of the previous researchers clearly distinguished the difference between these two variables; this could be the cause of disagreement. Despite the disagreement the Knothe time function is an accepted method to approximate dynamic subsidence (Peng, Ma and Zhong, 1992). The surface subsidence is dependent on gob compaction since the two are connected through a continuous medium and therefore the Knothe time function approximation is applicable to gob compaction as well.
Complete discussion of dynamic subsidence and dynamic gob compaction must also address the caving behavior of the immediate strata. The caving behavior is related to mechanical strength of the rock and bedding thicknesses of the immediate strata. Two mechanisms of caving were identified (Hill, 1995), parting-plane controlled caving and bulking controlled caving. When the immediate roof consists of massive units of strong, competent rock, parting-plane controlled caving occurs. A void between the caved waste and overlying strata will result from this type of caving. Bulking controlled caving occurs when the immediate roof caves and the rock fragments swell to completely fill the void space. Subsidence occurs as the overlying strata sags down on top of the rock fragments and compaction in the fashion described above occurs. The actual caving of the strata to form the gob is likely a combination between the two forms of caving behavior. At the start of mining when the immediate roof is not exposed to the full weight of the overburden the first form of caving will likely dominate. This has been observed at mines that have issues with a lagging cave near the start-up room as a result of massive, cantilevered units of strong overburden such as sandstone, siltstone or limestone. As the longwall progresses towards the recovery room the immediate roof is only supported by the shields. The ability to cantilever behind the shields is diminished as the roof is required to support the full weight of the overlying strata. The dominant mechanism of caving in this area is likely bulking controlled caving.

2.4 Introduction to porous media

A porous medium as defined by Nield and Bejan (2013) is the combination of an impermeable matrix and scattered with void regions. Permeability is a measure of the resistance to a fluid flowing through the porous medium. Everything from limestone to rye bread has been referred to as porous media. In natural porous media (Zeng & Grigg, 2006). The pores and the channels that connect these pores are irregularly spaced and sized. The flow behavior on the pore scale, or microscopic scale, will be highly irregular. When these pore flow quantities are averaged over areas that cover many pores, as done in some experiments, the macroscopic flow behavior becomes regular with respect to space and time. A common technique is spatial averaging and involves a representative elementary volume. The largest possible representative elementary volume should be used, yet it must be small enough to ensure fidelity to local averages on the microscopic scale are maintained. This size is larger than the pore size but much smaller than the length scale of the global flow domain; as shown in Figure 2.11. The macroscopic porous flow behavior of fluid is described using these representative elementary volumes and global measurements such as permeability or conductivity and porosity.
Tests by Pappas and Mark (1993) focused on determining the mechanical properties of caved gob material. The authors also discussed gob material size distribution. Figure 2.12 shows pictures taken of three Eastern coal mine gobs and a photo-analysis depiction of a Virginia coal mine gob. The purpose of the photo-analysis was to digitize the gob image to estimate a particle size gradation. One finding of this study was that the stress and strain behaviors of the gob could be scaled to larger gradations so long as the distribution remained the same. The determined size gradation is given in the form of a histogram in Figure 2.13. A correction factor was applied to the two-dimensional photograph to account for the three-dimensional nature of the gob material. The correction factor was determined by taking a pile of rock with a known size gradation and photographing the pile from all sides. Researchers noted that the photo analysis technique was an accurate prediction of size gradation however the amount of smaller grain sizes was under predicted. This technique is often applied to examine blasted rock piles and is an accepted method of determining gradation curves. Photoanalysis of the Virginia coal mine gob resulted in a mean rock fragment size distribution of approximately 2.5 inches and a maximum rock size of approximately 22 inches.
One difference between Eastern and Western U.S. coal mines is generally the amount of sandstone in the overburden; Eastern coal mines generally have more shale and mudstone. Due to a higher fracture strength the sandstone is generally stiffer than either mudstone or shale and will cave with a higher bulking factor. This bulking factor widens the size distribution of the caved gob material. During a visit to Mine E, a rock fragment several meters in diameter was observed while Mine C the gob caved in much smaller fragments, only several inches across. Several researchers including Whitaker (1986) and MacDonald et al. (1991) found that a wider size distribution often lead to a lower density due
to a ‘packing effect.’ The packing effect depicted in Figure 2.14 is a result of smaller fragments filling in the large voids left between large rock fragments. MacDonald determined that permeability tends to increase with larger particle sizes and decrease with large size distributions.

![Figure 2.14: Illustration of the ‘packing effect’ (Whitaker, 1986)](image_url)

2.4.2 Darcy’s law

Darcy (1856) observed there was a relationship between flow rate and the applied pressure difference. As noted by Bear (1972) Darcy’s findings as valid for the following conditions:

1. The porous media is homogeneous throughout
2. The flow is steady and one dimensional
3. The fluid is incompressible
4. Kinetic energy & inertial effects are negligible

Darcy’s law is given in Equation (2.5). The equation states that the pressure drop through a porous media is a function of the fluid viscosity, \( \mu \), the permeability of the medium, \( k \), and the velocity at which the fluid travels though the medium, \( v \).

\[
\Delta P = -\frac{\mu}{k} v
\]  

(2.5)

Darcy’s law is an excellent prediction for laminar flows but a number of researchers have shown that it begins to break down in the turbulent flow regime. According to Zeng and Grigg’s (2006) historical review of research on the subject of a critical Reynolds number that designates non-Darcy flow ranges from 1 to 70. Ergun (1952) developed a Reynolds number specifically for porous media by including the particle diameter, \( D_p \), the porosity, \( n \), and the velocity of fluid in the pores as shown in
Equation (2.6). From Ergun’s research of gas flow through packed particle media a critical transition to non-Darcy flow was seen at a Reynolds number from $3 \rightarrow 10$. Nield and Bejan (2013) state Darcy’s law is only valid for Reynolds numbers below one.

$$Re = \frac{\rho D_p v}{\mu} \left( \frac{1}{1 - n} \right)$$  \hspace{1cm} (2.6)

The transition from Darcy to non-Darcy flow is characterized by non-linear drag and is smooth. As $Re$ is increased from $1 \rightarrow 10$ there is no sudden jump to turbulence. Hlushkou and Tallarek (2006) determined the additional inertial drag not accounted for by Darcy’s law, was not caused by turbulence which was not observed until Reynolds numbers two orders of magnitude higher than deviation from Darcy’s law was seen. Forchheimer (1901) first discovered the presence of this additional drag and found that the flow in the pores themselves was still laminar. The additional drag is a result of the form drag due to solid obstacles being on the same order as the surface drag due to friction. Forchheimer’s modification to account for this additional drag is given in Equation (2.7. This is the version recommended for use by Nield and Bejan (2013), however, the form drag constant term, $c_F$, must be determined experimentally for various porous media.

An alternative formulation was developed by Ergun (1949). Ergun specifically investigated the non-linear relationship between fluid velocity and pressure gradient for gas flow through crushed rock fragments. He developed a relationship that accounts for the flow rate, the properties of the fluid, the porosity of the medium and the size, layout and geometry of the particles within the porous media. He generalized the Forchheimer equation to obtain the formulation given in Equation (2.8. This formulation is depicted in comparison to Darcy’s law in Figure 2.15. The Ergun formulation was validated experimentally by Macdonald et al. (1979) and Papathanasiou (2001). Ward (1964) found the Ergun equation to cover a wide range of velocities in porous media creeping to turbulent flow with good agreement to experimental data.

Note that the Ergun equation is the method used by Fluent to account for the non-linear drag. Fluent’s formulation of porous media flow is to add the source term given in Equation (2.9 to the momentum equation. The first term accounts for the laminar losses and the second term accounts for the non-linear form drag. Worrall (2012) showed that, when the only first term is included as the sole source term in the momentum equation, the relationship reduces to Darcy’s law.
2.4.3 The Carmen-Kozeny equation

A macroscopic description of porous media requires two macroscopic properties: porosity and permeability. The porosity is defined as the ratio between the total volume of voids or pores and the total bulk volume. Effective porosity considers only those voids that are interconnected and permit fluid flow through the porous medium. There have been several attempts to develop a relationship for determining permeability as a function of porosity, the first and most commonly used approach is the Carman-Kozeny equation (Kozeny, 1927 and Carman, 1937). The derivation is based on the following key assumptions after (Bear, 1972):

\[
\Delta P = -\frac{\mu}{k}v - \frac{c_F}{\sqrt{k}} \rho |v|v
\]  
(2.7)

\[
\Delta P = -150 \frac{\mu (1 - n^2)}{d_p^2} v - 1.75 \frac{\rho (1 - n)}{d_p n^3} |v|v
\]  
(2.8)

\[
\Delta P = -\left(\mu v + 1.75k \frac{\rho (1 - n)}{D_p n^3} |v|v\right)
\]  
(2.9)
1) Porous media is simplified into a bundle of capillary tubes of equal length
2) The tubes can be of any cross section but the cross section remains constant
3) The flow is laminar and steady
4) Flow is one directional and normal to the direction of the channel
5) The fluid is Newtonian and incompressible

The original equation developed by Kozeny (1927) is given in Equation (2.10). The Kozeny constant, $c_o$, accounts for the geometry of the capillary tubes themselves, $n$ is porosity and $M_b$ is the interstitial surface area of the pores per unit of bulk volume. Carmen’s modification uses a Kozeny constant of 0.2 and evaluates the interstitial surface area of the pores per unit of solid material, $M_s$, rather than bulk volume resulting in Equation (2.11). Esterhuisen and Karacan (2007) presented a version used in reservoir engineering with constants derived from the Pappas and Mark (1993) size distribution of caved gob fragments; this version is given in Equation (2.12). The initial permeability, $k_o$, should be $1 \times 10^6$ which places it in the range of “open jointed rock” according to Hoek and Bray (1981).

$$k = \frac{c_o}{M_b^2} n^3$$  \hspace{1cm} (2.10)

$$k = \frac{0.2}{M_s^2 (1 - n)^2} n^3$$  \hspace{1cm} (2.11)

$$k = \frac{k_o}{0.241 (1 - n)^2}$$  \hspace{1cm} (2.12)

Karacan (2010) recommends the use of fractals. The formulation of fractals accounts for the tortuosity, i.e., ratio of the waviness or meandering of the channel compared to a straight channel, particle size and general cross section of the channel. The general theory underlying fractals is that many geometric shapes, even random shapes, eventually form a pattern and can therefore be described and modeled analytically. Karacan argues that fractals are the most appropriate method to determine permeability of the crushed gob material. A number of other researchers including Koponen et al. (1997), Yu and Cheng (2002), Yu et al. (2003), Yu et al. (2005), Wu and Yu (2007), Valdes-Parada et al. (2009) and Henderson et al. (2010) have used fractals to describe the permeability of a variety of porous media materials. Fractals have been shown to greatly outperform the Carman-Kozeny approach.

Valdes-Parada et al. (2009) concluded from experimental studies that flow through actual porous media is far too complex to be described by simple empirical equations such as the Carman-Kozeny equation. They suggested that the porosity in addition to the complex microstructures be used to determine permeability through porous media. The research by Karacan (2010), involved Hagen–Poiseuille flow
and estimated the fractal properties of the gob from reservoir engineering concepts. One cautionary note regarding fractals is that rigorous experimental testing is required to verify the parameters used. The only advantage of fractals over the more traditional Carmen-Kozeny approach is the internal consistency once parameters have been determined. No matter the methodology used to derive the permeability of the porous media analytical descriptions cannot replace measurements and rigorous validation through experimentation. Unfortunately at present given both the technical difficulty and regulatory stipulations measurement and testing inside the gob and behind the shields is difficult if not impossible.

2.5 Gob permeability and porosity

The permeability and porosity distributions in the gob are important for accurately determining the gas flow and air ingress into the gob. The gas flow models require the input of permeability and porosity to properly model flow through a porous media, such as the gob. Previous attempts to define the permeability of the gob include direct measurement, numerical modeling and empirical derivations from first principles. A summary of previous findings is presented in Table 3.4.

2.5.1 Laboratory tests and direct measurement

Laboratory tests by Jozefowicz (1997) proposed an interesting modification to the Pappas and Mark test. Tri-axially loaded samples were placed in a Hoek-Cell that also acted as a permeameter. As the samples were loaded, nitrogen gas was injected at the top of the sample at a known pressure and the volumetric flow rate of the gas was monitored. Darcy’s law was used to determine the intrinsic permeability at each confining pressure. The test consisted of eight samples including four sandstones, three shales and one gritstone. Jozefowicz developed a third degree polynomial curve representing permeability with volumetric strain given in Equation (2.13; \( \varepsilon_{V\text{ol}} \) is the volumetric strain of the gob and \( k_{\text{gob}} \) is the coefficient of permeability (m²)).

\[
k = -4 \times 10^{-16} \varepsilon_{V\text{ol}}^3 - 6 \times 10^{-15} \varepsilon_{V\text{ol}}^2 - 7 \times 10^{-14} \varepsilon_{V\text{ol}} + 1 \times 10^{-11} \quad [m^2]
\]

The concept of a coefficient of permeability, from direct in-situ measurements, was introduced by Szlązak (2001) to study airflow patterns in the gob for the purpose of spontaneous combustion mitigation. Laminar flow in the gob was assumed from observations at three mines. This assumption
allows the coefficient of permeability, k, to be calculated from the equation for linear filtration through porous media given in Equation (2.14 where $\mu$ is the co-efficient of absolute viscosity of air (Nsm$^{-2}$), $A_c$ is the cross sectional area of airflow (m$^2$), $\Delta p$ and L (m) are the pressure drop (Nm$^{-2}$) and distance between two measurement points, and $\Delta Q$ is volumetric airflow in the gob (m$^3$s$^{-1}$).

$$k = \frac{\mu L}{A_c \Delta p} \text{ [m}^2\text{]}$$  \hspace{1cm} (2.14)

2.5.2 Numerical models using FLAC$^{3D}$

Recent research involves numerical simulations to simulate the complexity of gob compaction. FLAC$^{3D}$ contains a Double Yield model capable of simulating the irreversible compaction of gob material in a fashion detailed above in section 2.3.2 (Use of FLAC3D to model longwall caving). Previous researchers (Badr, 2004; Yavuz, 2004; and Esterhuizen and Karacan, 2005) have also used FLAC's double yield model to simulate the gob compaction. Another researcher (Yavuz, 2004) published a method for determining the stress distribution in the gob and used FLAC$^{3D}$ to validate his findings. In his formulation he also describes how to determine the height of the gob given the site conditions. Further, extensive studies (Esterhuizen and Karacan, 2005; Esterhuizen, Mark and Murphy, 2010) determined the mechanical properties that should be used as a starting point for modeling the overburden and gob in coal mines. Even with these recommendations the properties assigned to the gob are site specific. Much of the work done by NIOSH in regards to gob modeling has focused on Eastern coal seams. Caving characteristics of every mine differ and visits of several Western US mines (Worrall et al., 2012) revealed a void that forms between the gate road system and the gob. Mechanical properties of the overburden should be determined through lab tests and de-rated to account for rock mass properties, the gob properties are more difficult to determine. In order to match the subsidence profiles from a specific site given known strengths of the overburden, the gob properties must be altered to validate the model with field measurements.

Porosity is determined from the compaction, or volumetric strain, of the gob material computed in FLAC. The compaction of the Double Yield gob elements is taken as a one to one reduction in porosity. The initial porosity should be defined as the void volume, which can be calculated from knowledge regarding the determined caved zone height, extraction height of the panel, and the inherent porosity of the immediate overburden that will make up the gob. An empirical relationship between permeability and porosity is the Carmen-Kozeny relationship given in Equation (2.15 where K is permeability (m2), Ko
is the base permeability \((m^2)\) of the rock and \(n\) is the porosity \(\%\). This approach has been used by others (Esterhuizen and Karacan, 2007; Lolon, 2008).

\[
k = \frac{K_o}{0.241 \left( \frac{n^3}{(1 - n)^2} \right)}
\]  

(2.15)

2.5.3 Fractured zone

The porosity and permeability distributions of the fractured zone have been studied using a variety of methods. FLAC2D (Esterhuizen and Karacan, 2005) has been used to simulate the stress change, extent of rock fracturing and bedding plane shear to determine permeability changes from empirical relationships. The models were used to investigate the rock behavior above the longwall and near startup and recovery rooms. The failure mode (compression or shear) was used to predict the change in permeability of the rock mass and an exponential relationship was used to determine the effect of stress on the permeability. A series of drawdown and decline curve analysis tests (Dougherty, Karacan and Goodman, 2010) was used to determine gob reservoirs and study the effectiveness of gob vent boreholes (GVB). The conclusion was that high permeability was initiated by compressive stresses ahead of the face and fractures induced by tensile stresses behind the face.

2.6 Use of CFD to investigate coal mine ventilation hazards

There have been numerous efforts to research the interaction between ventilation air and in-situ gob gases in order to further understand mine gas distributions and methane accumulation in mines. The studies have been empirical and numerical in nature. Experimental methods employ the use of monitoring tools and tracer gases to track fluctuations in gas concentrations through the mine. Empirical methods use direct mine measurements to develop equations, from first principles, to describe airflow through the mine. Most of these previous numerical modeling efforts have used some form of CFD software, reservoir modeling software or ventilation network flow models. Numerical models have been favored for gob studies as the inaccessibility makes accurate readings difficult to obtain. A realistic initial input of permeability and porosity distributions is required for numerical models and one of the approaches outlined in the above section should be used.

Classical numerical models are in the form of network flow models. The benefit of these models is the quick model run times and simple set-ups, allowing the user to quickly define and solve a model for
a mine scale problem. These simple network models assume laminar flow and greatly simplify gas diffusion. The gob is characterized by flow through porous media and the size, shape and extent of gas mixtures is important in characterizing explosive potential and oxygen ingress into the gob to assess spontaneous combustion potential. Further, simple network flow models cannot model in sufficient detail the effectiveness of inert gas injection in regards to gob hazard mitigation. Network flow models do not give enough detail for research studies regarding large, open areas of the mine, particularly the gobs.

Numerical models such as CFD or reservoir flow models allow for greater detail regarding flow characteristics and are more appropriate for modeling the gob environment. The modeler has more flexibility regarding model geometry, multiple flow regimes (laminar, turbulent and transitional) and the reaction and mixing of species. Benchmark testing proved the validity of CFD to capture mine air behavior by showing that the simulation results matched experimental data (Wala et al., 1997). More recent benchmarking proved that CFD simulations could match the methane distribution in a longwall panel obtained from experimental results (Wala et al., 2007). Innovative approaches to using CFD analysis in mining will be introduced followed by a critique of previous efforts.

CFD models have studied the interaction between gob gas, mostly methane, and incoming ventilation air. This topic is an area of great interest given that the disaster at the Upper Big Branch Mine was initially caused by a methane ignition near the tailgate corner of the longwall. Worrall (2012) developed a unique algorithm to display explosive volume using a user-defined function. The algorithm takes the resulting mixtures of methane and oxygen calculated by Fluent and relates the gas concentrations to explosibility per Coward’s triangle. The algorithm also calculates the total volume of the explosive mixture. This algorithm was further used to optimize nitrogen injection for a completed longwall panel in the process of recovery. Worrall’s work included a face ventilation rate study and a simulation of the sealing of a longwall panel by taking steady state snapshots in time. He concluded that increased face ventilation diluted methane in the tailgate return but also led to increased face air migration into the gob. The increased leakage of face air led to an increase in the explosive gas volume in the gob. The results of Worrall’s studies are given in Figure 2.16. An important aspect of his work was the inclusion of a “void” around the edges of the gob that was evident from several mine visits and is detailed further in his work. The model was also used to study the effect of nitrogen injection location and to optimize the injection rate for this particular mining situation. The nitrogen injection was optimized to minimize explosive gas volumes (Marts et al., 2013) and oxygen ingress into the gob.
A key finding of the nitrogen injection optimization study is given in Figure 2.17. Another CFD model was constructed to model the tailgate ventilation (Brune and Sapko, 2012) effects on methane distribution near the tailgate. The study determined that tight caving in the return had the potential to reverse airflow creating an acute explosion hazard. The study also concluded that explosive mixtures of methane could reach the longwall shearer and would potentially not be detectable by sensors located on the shearer or on the tailgate drive.

Spontaneous combustion is another topic where CFD modeling is used extensively. In spontaneous combustion prevention, oxygen ingress into the gob is the primary concern. CFD modeling was used to investigate the airflow and oxygen ingress into the gob for various ventilation schemes (Yuan, Smith and Brune, 2006). This research concluded that sudden changes in airflow resistance, such as a cave in, could result in a critical airflow velocity zone suitable for the onset and promotion of spontaneous combustion. Further spontaneous combustion research (Yuan and Smith, 2008) focused on the effects of ventilation and gob characteristics on spontaneous heating. The two factors researched were pressure differentials across the gob and gob permeability variation. The study concluded that increasing the pressure differential across the gob increased the rate of spontaneous combustion. Additionally, permeability was inversely proportional to induction time. Input parameters and solver settings for models developed to study spontaneous combustion were refined and calibrated by using CFD to study spontaneous heating in a large-scale coal chamber (Yuan and Smith, 2009). The purpose was to refine previous attempts for mine scale modeling of spontaneous combustion. The CFD model was calibrated against US Bureau of Mines tests (Smith, Miron and Lazzara, 1991). Recent spontaneous combustion research has used the refinements developed in their 2009 model to investigate the effects of face advance rate (Yuan and Smith, 2010) and seal leakage (Smith and Yuan, 2010). Rapid face advance was found to quickly reduce maximum temperatures developed following a face stoppage but at greater distances inby, the face advance had little effect on temperature. Lolon (2008) found that in bleeder panels the hot spot originated near the bleeder shaft and that longer panels both increased the size of the hot spot on the tailgate side and promoted the formation of a hot spot near the face, directly behind the shields. Lolon (2008) also found that a progressively sealed panel configuration significantly reduced the size of the hot spots and only one was observed, directly behind the shields. The spontaneous combustion research using CFD mentioned in this paragraph all used a gob permeability distribution that was determined using the Carmen-Kozeny approach.
Figure 2.16: Impact of Face Flow Rate on Relative Hazardous Mixture Volume and Methane Concentration in the Tailgate Return (Worrall, 2012)

Figure 2.17: Nitrogen injection location and quantity effects on explosive gob gas volume (Worrall, 2012)
CFD models have also been used to study gob gas control (Ren, Balusu and Humphries, 2005),
gob inertization (Ren and Balusu, 2005), and even air and dust flow patterns around the longwall
shearer (Balusu, Chaudari and Ren, 2004). All of the gob research models include important mine safety
technologies such as GVBs and nitrogen injection. Fluent’s built in porous media model was used and a
UDF was created to apply the Carmen Kozeny porous media distribution. Figure 2.18 shows the results
of a nitrogen injection location study from Ren and Balusu’s (2010) model. During modeling, it was
noted that immediately behind the face, roughly 50 – 150m, the gas distributions were dependent on
face flow rates and pressure, while further back into the gob and in upper levels of the model
distributions were more dependent on buoyancy effects. Simulations also determined there was no
difference if the inert gas was modeled as nitrogen or Tomlinson Boiler gas.

Figure 2.18: CFD Results of Inertization Simulation (Ren and Balusu, 2010)
The purpose of the research by Ren and Balusu (2010) was to develop guidelines for Australian mines using nitrogen injection and GVBs. Recommendations to mine operators included basic ventilation changes, panel sealing schemes, GVB operation, and nitrogen injection guidelines. They included the following recommendations:

- Bleeder ventilation schemes are not advisable for spon com prone mines
- Immediate sealing of cross cuts behind the face, leaving one open for the back return (Balusu et al., 2005)
- Uniform and continuous GVB operation at a lower vacuum is more efficient than “on/off” operation (Balusu et al., 2005)
- Tailgate inert gas injection is not as effective as headgate injection (Ren and Balusu, 2010)
- Reducing the quantity results in significantly lower leakage into the gob (Ren and Balusu, 2010)

Recommendations in regards to inert gas injection, GVB operation and panel sealing strategies are as follows:

**N2 Injection Guidelines (Ren and Balusu, 2010)**

- Best to inject into the gob at 200 to 400m behind the face, or in-by side of a suspected heating location in the gob
- Flow rate of around 0.5m$^3$/s is recommended for most cases
- Inject on headgate side of the gob is more effective in most cases
- Inject on both sides of the gob if heating is suspected on the tailgate side of the gob
- Continue injection until face resumes normal production in case of prolonged stoppages or until face has retreated for more than 300 to 500m past the suspected heating location, in the case of advanced heating events

**Panel Sealing Inertization Strategy Guidelines (Ren, Balusu and Humphries, 2005)**

- Inert gas should be injected into the gob at around 200m behind the face finish line, i.e., at an in by location with respect to explosive fringe in the gob
- Inert gas should be injected on the headgate side of the gob or on both headgate and tailgate sides
- Inert gas injection should start at least 1 or 2 days before panel sealing, with minimum ventilation flow and doors on return seal still open
- Inert gas flow rate of 0.5 to 1.0m$^3$/s is recommended, subject to implementation of all these optimum strategies
- Inert gas injection to be continued after sealing until O$_2$ levels are below 8%
GVB Operational Guidelines (Ren and Balusu, 2010)

- Drill GVBs on the tailgate side, roughly 30 – 70m from the gateroads depending on
  caving, spaced at 100 to 300m depending on gas emissions
- Capacity should be roughly 2 -3 times gas emission expected
- Multiple GVBs reduces the effects from barometric pressure changes
- Continuous operation is recommended
- Vacuum pressure set at a level to reduced oxygen ingress into the gob, no more than 5%
  oxygen concentration to reduce spon com risk

A significant amount of research from both NIOSH and the US Bureau of Mines has focused on GVB
operation. Their findings and recommendations are given below.

- Location is important GVBs placed near the startup room have the highest cumulative
  production for the longest duration. This is likely from incomplete caving near the
  startup room (Diamond, 1994)
- Height above the mined coal seam is a crucial design parameter. Ensuring the slotted
  casing is located in the fractured zone and adjacent to gas bearing strata but far enough
  away from the seam to prevent excessive production of face ventilation air is important.
  This will maximize methane drainage (Karacan et al., 2007a; Karacan and Goodman,
  2009)
- Increasing the GVB diameter increases cumulative methane drainage production due to
  lower friction losses (Karacan et al., 2007a)
- Increasing the length of the slotted casing interval increases methane recovery, as long
  as the slotted interval remains in the fractured zone (Karacan et al., 2007a)
- Development and application of stochastic models to assess methane content in coal
  seams and simulate GVB effectiveness for a range of geological and mining features
  (Karacan, 2007; Karacan, 2009d; (Karacan and Luxbacher, 2010; Karacan and Goodman,
  2011)
- Faults act as impermeable barriers to methane flow. Once the fault is undermined by
  the longwall the GVBs ahead of the longwall begin production once the fractured zone
  begins to develop. Faults can also lead to pressure buildup and cause outbursts of gas
  when mining through the fault (Karacan, Ulery and Goodman, 2008)
- A higher suction pressure has a positive but small impact on gas production from GVBs
  (Karacan, 2009c)
- Placement of GVBs in the regions that experience the maximum tilt in respect to surface
  subsidence maximizes methane drainage production. These areas correspond to areas
  near the gateroads of the panel (Schatzel et al., 2012)
- Geostatistical modeling of in-place gas content to determine best placement of GVBs in
  Pittsburgh seam coal mines (Karacan, Olea and Goodman, 2012)
The gob and fractured zone may also be treated as a gas reservoir, allowing the use of reservoir modeling tools. Fracturing and movement of the overburden resulting from mining activities changes the reservoir properties of intact rock and methane reservoirs. Understanding how the methane migrates towards active workings requires knowledge of flow paths and dynamic reservoir properties which can also be used to optimize GVB locations and design. A reservoir modeling software package, GEM, was used by Karacan et al., (2007a) to characterize longwall methane emissions and evaluate designs for GVBs. The modeling was completed using “restart runs” or pseudo transient snapshots with input from the geo-mechanical model. To verify the results the model was calibrated against production history curves of GVBs. Further research by Karacan, Ulery and Goodman (2008) investigated the effects of impermeable faults. It was concluded that in a faulted coal seam, the locations of GVBs are important and their area of influence does not extend beyond the fault. Understanding gained from the reservoir model was used in field tests to characterize GVB performance. Multiple rate drawdown well tests were used by Karacan (2009c) to further define the behavior of GVBs and reservoir properties of the gob. Specifically the study investigated the effects parameters such as skin, permeability, radius of influence and flow efficiency have on GVB flow efficiency. A field study of dynamic reservoir response (Schatzel et al., 2012) confirmed the trends found using the reservoir modeling approach. In addition to confirming the validity of using the reservoir model surface subsidence was also used to determine the best placement of GVBs. Using results from the well tests and geo-mechanical output it was concluded that maximum overburden permeability region, in the fractured zone, should occur in the region of maximum tilt of the surface and area of greatest gob compaction.

2.7 Summary and conclusions from the literature survey

Previous attempts to model the gob compaction serve well as initial guidelines for modeling purposes. The experimental (Pappas and Mark, 1993) gob compaction stress strain curves verified the strain hardening behavior. The mechanical strength properties and behavior of a gob are site dependent. The primary mechanical properties governing gob compaction have varied greatly between rock types and geographical location (Salamon 1990, Esterhuizen and Karacan 2005 and Wachel 2012) and are difficult to determine for lack of direct measurements. The effect of dynamic gob compaction also needs to be further resolved. Dynamic subsidence is well understood and can be measured. Dynamic gob compaction cannot be measured and is best determined from numerical modeling. A sequential extraction model (Esterhuizen and Karacan, 2005) was done in 2-D and focused primarily on
the dynamic changes to reservoir conditions in the fractured zone and overlying layers. A 3-D model (Esterhuizen and Karacan, 2007) to simulate gob compaction for the purpose of GVB studies was modeled with the coal being extracted in a single step. Single step models have been shown to produce gob compaction that is symmetric from start-up room to recovery room, while USBM studies suggest this may not be reality for active longwalls, see Figure 2.10.

To ensure these geo-mechanical models are useful for researchers using a variety of gas flow simulations, a universal curve fit is required, detailing the permeability and porosity distributions. Further refinement from a previous model is needed due to the absence of side, front and back abutment pressures that are known to exist around the edges of mined areas. Karacan (2010) developed a fractal model to refine the relationship between porosity and permeability, however, this model is difficult to implement in either CFD or reservoir models. It predicted values that are similar to predictions using the Carmen Kozeny relationship (Esterhuizen and Karacan, 2007).

Previous research simulating the flow in and around the gob area has relied on calibrating models against tube bundle readings and GVB production data. Gas flow models, particularly CFD models, require necessary simplifications when modeling large and complex environments such as a longwall gob. Reservoir modeling software was not designed to resolve flow through non-porous media such the longwall face. Simplifications to resolve this issue include assigning the void space 100% porosity and a minimum allowable resistance while entries were modeled as fractures, using the extraction ratio as detailed by (Esterhuizen and Karacan, 2007). When porosity is set to 100% the governing equations simplify to laminar flow which has been shown to affect results (Worrall, 2012). The effects of modeling entries as fractures could not be compared. Gravity is important due to buoyancy effects and gas mixing deep inby the gob, but it does not affect flow near the face which is dominated by momentum driven flow. A study by Ren and Balusu (2010) determined that gas distributions near the face were dependent on face flow rate and pressure while buoyancy had some effect on the flow and gas distributions farther back into the gob and in upper levels of the model. The permeability and porosity distributions must also be reasonable to obtain reasonable results from the CFD model. The distributions are normally presented in the shape of a ‘bathtub’ graph with maximum compaction occurring in the center of the panel and compaction decreasing to a minimum around the edges of the panel. This distribution results in a ‘bowed’ profile of oxygen ingress into the gob. The profile is the result of pressures near the intake of the model sufficiently high to drive face air into the gob. After a sufficient distance along the longwall face, the face air pressure has dropped enough for the leakage to reverse. Balusu’s models do not
capture this effect as evident in Figure 2.18. During several mine visits continuous open voids were observed along the gateroads (Worrall et al., 2012). Modeling sensitivities on void inclusion showed significant differences (Worrall, 2012). The voids have also been observed at two longwall coal mines and a longwall trona mine. It is evident from the results presented by Balusu that the permeability distribution he used does not include this void.

Another issue with much of the CFD research is the sole focus is on oxygen ingress. While oxygen ingress is important to control in spon com prone mines, there is also a concern with methane mixing with face air leaking into the gob. Worrall (2012) was able to study the effects of methane and oxygen mixing in the gob. Work completed by other researchers discussed in this section does not detail modeling selections, convergence criteria and grid refinement studies and it is unclear how their selections affect the final results and predictions of the model. A previous study regarding active longwall faces have only modeled the interaction with GVBs and focus primarily on the fractured zone (Karacan, Ulery and Goodman, 2008). The active face model was calibrated with GVB production data rather than gob data and therefore may not be accurately representing the gob.
CHAPTER 3
GEOMECHANICAL MODELING OF CAVING USING FLAC3D

This chapter details geo-mechanical modeling approach used to derive the porous media properties required to model gas distributions and flow in the gob. The first section introduces the two partner mines that the model was calibrated against. The next section focus on FLAC3D and the constitutive models used for the geo-mechanical model. The third section investigates the model sensitivity to parameters required in each of the constitutive models. The fourth section describes the gob compaction modeling process and the stepped extraction method used to capture the dynamic effects of an advancing longwall face and concludes with validation of the model. The fifth section presents the results of the geo-mechanical model and describes how the output from the geo-mechanical model is converted into porous media properties. The final section summarizes the findings from the geo-mechanical modeling effort.

In this study, the program FLAC3D is used to simulate the compaction of the gob during active longwall mining in order to determine the dynamic reservoir properties associated with an active panel. FLAC3D was specifically developed for geo-mechanical analysis of soil and rock in three dimensions. In addition to the standard Mohr Coulomb model, two constitutive models are provided in the FLAC3D software: the Ubiquitous joint and the Double Yield models. Expanding on their earlier work Esterhuizen et al., (2010) showed the stress distribution in the gateroad pillars was accurately captured with this approach. This model only considered a steady-state approach and did not capture the dynamic effects associated with an advancing face, namely ‘creep’.

3.1 Cooperating mines

Two Western U.S. coal mines, Mine C and Mine E, provided information that was used to calibrate the gob compaction model. The average depth of cover at Mine E is 120m compared to 140m at Mine C. Both mines operate supercritical panels. The extraction heights are 2.9m at Mine E and 3.35m at Mine C. The seam in Mine E is immediately overlain by a massive sandstone with a high RQD. Mine C is immediately overlain by weaker mudstones and shales that will form the gob. The sandstone gob should exhibit a stiffer compaction response compared to the mudstone and shale gob. Reported average final subsidence values for each mine are 58% of the extracted coal height at Mine E and 77% at Mine C,
implying that Mine C caves much tighter than Mine E. From observations made during site visits to each mine the bulking factor at Mine E appears to be larger than at Mine C. In Mine C, the gob consists of small rock fragments, the largest of which appeared to be smaller than 1m. At Mine E, the gob consists of larger sandstone fragments, a block several meters across was observed near the tailgate. The extent and boundaries of the caved and fractured zones were determined from data provided by the mines.

3.2 Background on $FLAC^{3D}$

$FLAC^{3D}$ is a three dimensional numerical modeling program that relies on the explicit finite difference method for modeling soil, rock, or other materials that exhibit plastic behavior once their yield strength has been exceeded. The program is versatile in its definition of geometry, boundary conditions and material properties. Rock is represented in $FLAC^{3D}$ as a Lagrangian or deformable mesh of grid points. Each element can be modeled to exhibit either elastic or plastic behavior. Materials behave according to a stress-strain law, defined by constitutive models, in response to boundary constraints and applied forces. The continuum nature of the model is beneficial for reducing calculation times and is conducive to modeling large mine layouts such as a longwall panel.

Benefits of using $FLAC^{3D}$ for this research are primarily due to two constitutive models. The Double Yield model allows the gob to be simulated as a strain hardening material as predicted by the Pappas and Mark (1993) test discussed in the literature survey. In addition, the Ubiquitous joint model can simulate anisotropic mechanical strength and thus the behavior of rock mass.

3.2.1 The Mohr Coulomb model

The Mohr Coulomb model is the simplest representation of rock or soil behavior. Most numerical simulations model the rock mass as a Mohr Coulomb material since it fulfills the needs of most engineering problems. Failure is governed by the Mohr Coulomb failure envelope, given in Figure 3.1, which is a combination of Mohr’s circle and Coulomb’s friction law. The Mohr Coulomb model results in a linear elastic-perfectly plastic behavior as seen in Figure 3.2. The failure envelope is defined by the Mohr Coulomb failure criterion depicted by a bold line as well as a tension failure criterion depicted as $\sigma_t$. The material behavior is elastic inside the failure envelope and plastic yielding occurs when the stress state is equivalent to the failure envelope. The material cannot have a stress state outside the failure envelope. When tensile failure is predicted in the zone, the tensile strength in this zone remains
constant unless a brittle material is specified. If tensile failure is predicted in a brittle material the material undergoes instantaneous tensile softening and the tensile strength is set to zero in that zone. The shear failure mechanism for the Mohr Coulomb model is given in Equation 3.1 where \( c \) is the cohesive strength of the rock and \( \phi \) is the internal angle of friction.

One of the shortcomings of the Mohr Coulomb model formulation is the isotropic response. The Mohr Coulomb response is unrealistic to use for typical rock strata as fractures and joints characterize the rock mass behavior. Also, the Mohr Coulomb post-peak yield behavior is not appropriate: failure in the Mohr Coulomb model is plastic-elastic and plastic flow is initiated once the yield point strength is exceeded. To properly model the gob, strain hardening behavior is required.

3.2.2 The Ubiquitous joint model

The Ubiquitous joint model is a plasticity model that allows the user to specify shear weakness planes at a specific orientation and strength. These weakness planes or joints are embedded inside the solid matrix of rock mass and cause anisotropic mechanical strength. The addition of these weak planes inside a Mohr Coulomb rock mass better simulates the deformation. The user may specify softening and hardening properties of both the weak planes and the solid matrix. The Ubiquitous joint model assigns two different sets of material strength parameters. The first set is applied to the solid rock matrix while the second set is applied to the joints themselves. The behavior of the solid matrix is governed by the Mohr Coulomb failure criterion. The formulation of this model in FLAC\(^3\text{D}\) first determines if general Mohr Coulomb failure occurs and assigns the associated plastic response according to the Mohr Coulomb model. The stresses are then re-evaluated for failure along the weak planes of the joints. The program determines failure in this order to improve calculation speed. If the stronger rock mass fails then failure along the weaker joint will also occur. Failure along a joint in FLAC\(^3\text{D}\) is handled in the same manner as brittle tension failure in the Mohr Coulomb model, i.e., by means of an instantaneous tensile softening. Shear is the only mechanism through which the joints fail. Therefore the Mohr Coulomb shear failure equation is valid so long as the cohesion and friction angle of the weak joint is used.

\[
\tau = c + \sigma \tan \phi
\]  

(3.1)
The Ubiquitous joint model represents joint sets in the rock mass that act as discontinuities in the rock mass. These discontinuities influence the mechanical behavior of the rock mass since the joint is weaker than the surrounding rock mass when subjected to shear loading. As a result the stress and deformation pattern is modified giving an anisotropic response. The Ubiquitous joint model is assigned to every layer included in the strata above the coal seam.
3.2.3 The Double Yield gob model

With the Double Yield model of the FLAC\textsuperscript{3D} software, it is possible to simulate the fully-caved gob as a strain-hardening, granulated material. This model can simulate the compaction of granulated materials under increased loading using a cap-plasticity criterion, meaning the strain is dependent on both the level of stress and the plastic strain in the material. The Double Yield model was created to represent materials that experience significant irreversible compaction in addition to shear yielding, such as hydraulically placed backfill or lightly cemented granular material. In addition to the shear and tensile failure envelopes in the Mohr Coulomb and Ubiquitous joint model, a volumetric yield surface, or “cap”, is implemented in the Double Yield model to capture permanent volume changes caused from the predicted stress. The surface is defined by a user-specified “cap stress” table and is independent of shear stress. Volumetric strain activates the hardening behavior specified by the cap pressure table. The Double Yield model does not allow the material to harden during elastic strain. Hardening occurs only during plastic volumetric strain.

The expression of Hook’s law in terms of principal stresses and strains is given in Equations (3.2)-(3.4, where $\varepsilon_{\text{el}}^1$, $\varepsilon_{\text{el}}^2$ and $\varepsilon_{\text{el}}^3$ are the elastic volumetric strain, convention is negative for compaction, in each of the three principal directions, $\sigma_1$, $\sigma_2$ and $\sigma_3$ are the stresses in each principal direction, $K$ and $G$ are the elastic tangential bulk and shear moduli.

\begin{align}
\sigma_1 &= \left( K + \frac{4}{3}G \right) \epsilon_{1,\text{el}} + \left( K - \frac{2}{3}G \right) \left( \epsilon_{2,\text{el}} + \epsilon_{3,\text{el}} \right) \\
\sigma_2 &= \left( K + \frac{4}{3}G \right) \epsilon_{2,\text{el}} + \left( K - \frac{2}{3}G \right) \left( \epsilon_{1,\text{el}} + \epsilon_{3,\text{el}} \right) \\
\sigma_3 &= \left( K + \frac{4}{3}G \right) \epsilon_{3,\text{el}} + \left( K - \frac{2}{3}G \right) \left( \epsilon_{1,\text{el}} + \epsilon_{2,\text{el}} \right)
\end{align}

Hardening occurs when the material plastically compacts and its plastic stiffness ($K_p$) increases. Plastic stiffness is defined as the slope of the stress strain curve created by plotting the values specified in the cap table. The predicted volumetric strain state is used to interpolate the table to determine if any adjustment to the stiffness is required. The Double Yield model was originally intended for materials such as backfill. In these materials, compaction forces the grains closer together and an increase in the stiffness would be expected. In loosely packed materials, such as the gob, the primary mechanism of compaction or strain is through compaction or reduction of void spaces in the loosely packed rock pile.
The elastic stiffness is increased by modifying the bulk and shear elastic moduli by a user defined constant, R, relating plastic strain to elastic strain. The constant, R, is defined as the ratio of plastic strain to elastic strain. Nearly all the strain is plastic as the gob cannot elastically recover after the load is removed. The value of R used in the geo-mechanical model was set at 100, to ensure only than 1% of the total strain hardening is elastic. The plastic stiffness is defined in Equation 3.5. The modifications to the elastic moduli are given in Equation 3.6 for the bulk modulus and Equation 3.7 for the shear modulus. In the equations $p_c$ is the cap pressure, defined by the user defined cap pressure table, $\epsilon_{V,P}$ is the incremental plastic volumetric strain, K and G are the initial bulk and shear moduli. The compaction and unloading cycles of a Double Yield material is depicted in Figure 3.3. As the volumetric strain increases, the deformation becomes increasingly plastic. The ratio of elastic to plastic deformation decreases as volumetric strain is increased due to modification of the elastic moduli.

Total volumetric strain is defined by the cap pressure table and is the summation of elastic and plastic volumetric strains. The plastic volumetric strain represents irreversible compaction. FLAC also checks for tensile and shear modes of failure. If volumetric yield is not predicted, the same shear and tensile plastic corrections as the Mohr-Coulomb model are applied. The zone cap pressure is updated for every iteration using linear interpolation of the user specified cap pressure table. As the volumetric strain increases, the material becomes stiffer and resists further deformation as shown in Figure 3.3.

$$K_p = \frac{p_c}{\epsilon_{V,P}} \quad (3.5)$$

$$K_{New} = \zeta K_p \quad (3.6)$$

$$G_{New} = G \frac{K_{New}}{K} \quad (3.7)$$

3.3 Model parameter sensitivity analysis and calibration

Each constitutive model requires the user to define several mechanical properties that ultimately determine the mechanical strength of the rock mass and the model’s response. Parametric studies of each variable were completed to determine the significance of each variable. Each variable
was evaluated on the criteria of achieving supercritical behavior with an abutment angle of 21 degrees. Values published by Esterhuizen and Karacan (2005) and Esterhuizen et al., (2010) for the purpose calibrating FLAC\textsuperscript{3D} numerical models to study Eastern coal mines were used as a starting point.

3.3.1 Ubiquitous joint model parameters

The overburden strata was modeled using the Ubiquitous joint model. The orientation and strength of the planes of weakness are defined separately from the matrix properties and can also exhibit strain softening behavior. The partner mines provided laboratory rock strength testing results. The laboratory rock strength was converted to in-situ rock mass strength using the relationship suggested by Hoek and Brown (1980) as shown in Equation 3.8. In Equation 3.8, $\sigma_{50}$ is the strength of the laboratory sample in MPa and $d$ is the field-scale sample diameter in mm. The strength of a 1,000 mm diameter field sample would be 0.58 times that of the laboratory sample assuming a 50 mm laboratory sample diameter

$$\sigma = \sigma_{50} \left( \frac{50}{d} \right)^{0.18}$$

(3.8)
The strength of the joints was taken from a study by Esterhuizen and Karacan (2005) describing the numerical modeling of longwall coal mines using FLAC3D. The gob properties used for this portion of the calibration process were taken from a preliminary Mine C model that modeled the overburden as a Mohr Coulomb material.

No data was available for the joint shear strength of the bedding planes, a parametric study was completed to determine the effect of bedding strength on the model response. The parameters used for the joint shear strength study were taken from Esterhuizen et al., (2010) and are listed in Table 3.2. The joint dip was set at 30 degrees according to data provided by Mine E (Agapito, 1988). The panel was oriented perpendicular to the joint set, a technique recommended by Agapito (1988) to aid the caving process. The results given in Figure 3.4 depict the surface subsidence profiles for each of the joint strengths. The sensitivity of the model’s prediction of surface subsidence to joint strength is negligible even from “Very Strong” to “Very Weak” joint strength as defined in Table 3.2. The sensitivity of the gob displacement, measured from the top of the gob, was also independent of joint strength.

Figure 3.4: Impact of joint strength assignment on model prediction of surface subsidence
Table 3.1: Overburden strata mechanical properties used in FLAC3D calibration study.

<table>
<thead>
<tr>
<th>Group</th>
<th>Depth (m)</th>
<th>K (MPa)</th>
<th>G (MPa)</th>
<th>ρ (kg/m³)</th>
<th>c (Mpa)</th>
<th>Friction Angle (Degrees)</th>
<th>Dilation Angle (Degrees)</th>
<th>Tensile Strength (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OB 1</td>
<td>130</td>
<td>740</td>
<td>480</td>
<td>1,960</td>
<td>0.41</td>
<td>41.6</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>OB 2</td>
<td>120</td>
<td>1,720</td>
<td>1,270</td>
<td>2,400</td>
<td>1.04</td>
<td>40.9</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>OB 3</td>
<td>110</td>
<td>1,720</td>
<td>1,270</td>
<td>2,400</td>
<td>1.04</td>
<td>40.9</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>OB 4</td>
<td>100</td>
<td>690</td>
<td>520</td>
<td>2,550</td>
<td>0.77</td>
<td>27</td>
<td>14.6</td>
<td>0</td>
</tr>
<tr>
<td>OB 5</td>
<td>90</td>
<td>780</td>
<td>510</td>
<td>2,450</td>
<td>0.55</td>
<td>33.4</td>
<td>11.8</td>
<td>0</td>
</tr>
<tr>
<td>OB 6</td>
<td>80</td>
<td>1,190</td>
<td>890</td>
<td>2,490</td>
<td>0.94</td>
<td>32.9</td>
<td>12.8</td>
<td>0</td>
</tr>
<tr>
<td>OB 7</td>
<td>70</td>
<td>1,190</td>
<td>890</td>
<td>2,490</td>
<td>0.94</td>
<td>32.9</td>
<td>12.8</td>
<td>0</td>
</tr>
<tr>
<td>OB 8</td>
<td>60</td>
<td>940</td>
<td>700</td>
<td>2,520</td>
<td>0.86</td>
<td>30</td>
<td>13.7</td>
<td>0</td>
</tr>
<tr>
<td>OB 9</td>
<td>50</td>
<td>1,250</td>
<td>890</td>
<td>2,420</td>
<td>0.79</td>
<td>37.1</td>
<td>10.9</td>
<td>0</td>
</tr>
<tr>
<td>OB 10</td>
<td>40</td>
<td>1,690</td>
<td>1,270</td>
<td>2,430</td>
<td>1.11</td>
<td>38.8</td>
<td>10.9</td>
<td>0</td>
</tr>
<tr>
<td>OB 11</td>
<td>30</td>
<td>1,690</td>
<td>1,270</td>
<td>2,430</td>
<td>1.11</td>
<td>38.8</td>
<td>10.9</td>
<td>0</td>
</tr>
<tr>
<td>OB 12</td>
<td>20</td>
<td>1,440</td>
<td>1,080</td>
<td>2,460</td>
<td>1.03</td>
<td>35.8</td>
<td>11.8</td>
<td>0</td>
</tr>
<tr>
<td>OB 13</td>
<td>10</td>
<td>1,500</td>
<td>1,080</td>
<td>2,390</td>
<td>0.88</td>
<td>40.1</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>OB 14</td>
<td>0</td>
<td>1,070</td>
<td>700</td>
<td>2,380</td>
<td>0.56</td>
<td>38.4</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.2: Range of joint strength typical in coal measure strata (Esterhuizen and Karacan, 2005)

<table>
<thead>
<tr>
<th>Type of Joint</th>
<th>Cohesion (Mpa)</th>
<th>Friction Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Weak</td>
<td>0.05</td>
<td>21</td>
</tr>
<tr>
<td>Weak</td>
<td>0.5</td>
<td>21</td>
</tr>
<tr>
<td>Moderate</td>
<td>3.3</td>
<td>24</td>
</tr>
<tr>
<td>Strong</td>
<td>5.5</td>
<td>26</td>
</tr>
<tr>
<td>Very Strong</td>
<td>10</td>
<td>28</td>
</tr>
</tbody>
</table>

3.3.2 Double – Yield model parameter calibration

This section presents the Double Yield model parameter sensitivity analysis. Parameters are evaluated within published ranges and the model response is evaluated to determine how sensitive the model is to parameter variation. Discussion regarding model validation is presented in section 3.4.3.

Implementation of the double yield model requires the user to specify a “cap pressure” table or a series of data points that, when plotted, resembles the curve shown in Figure 3.4. In addition to the table, the user must also specify mechanical properties including bulk and shear moduli (K and G), density, friction angle, dilation angle, cohesion and tensile strength. A subroutine was written to allow K and G to be specified in terms of Young’s Modulus I and Poisson’s ratio (v). The relationship for bulk
modulus is $K = \frac{E}{3(1-2v)}$ and the relationship for shear modulus is $G = \frac{E}{2(1+v)}$. The actual parameters for a gob cannot be measured directly. They will vary from mine to mine depending on the immediate roof strata that cave to form the gob. Since the gob is made up of broken rock, cohesion and tensile strength of the rock mass are zero and nearly all deformation is plastic. The rock mass density is determined from the initial density of the immediate roof involved in the caving process. This initial density is decreased to account for the bulking factor of the gob. An initial bulking factor of 3 was used in this model based on a study by Esterhuizen and Karacan (2005) and data provided by Mine C. The remaining parameters (Young’s Modulus, Poisson’s Ratio, friction angle, dilation angle and hardening parameters) were varied in the sensitivity analysis.

The cap pressure table was created by using equation (2.1 developed by Salamon (1990) relating stress to volumetric strain of the gob. This hyperbolic equation represents the strain hardening behavior of the gob. Esterhuizen (2013) revealed that the $a$ parameter can be varied to obtain a match with subsidence curves. The $b$ parameter is related to the swell factor of the gob and inherent porosity of the immediate roof.

The calibration of the double yield parameters required parametric studies of Young’s Modulus, Poisson’s Ratio, friction angle and dilation angle. The purpose of the parametric studies was to determine the sensitivity of each variable on the subsidence and gob compaction predicted by the model. Impact on subsidence was evaluated as actual subsidence measurements were provided by the two mines. Impact on gob compaction was evaluated because this is a direct measure of volumetric strain which was used to determine the porous media properties of the gob. The initial cap pressure table was created using $a = 5.9\text{Mpa}$ and $b = 0.44$ (Esterhuizen et al., 2010). These values only predicted approximately 1.2m of subsidence. Calibration of these variables determined from the actual subsidence measured at the mine required adjustment of these variables to $a = 0.925\text{Mpa}$ and $b = 0.44$.

The targets used to calibrate the model include total subsidence and distance required for the panel to reach full subsidence conditions. Full subsidence was set at 2.66m from data provided by Mine C. The target distance at which the panel exhibits full subsidence is 84m from the edge of the panel and indicated by the dashed black line marked as “target”. This value was determined from a relationship relating supercritical behavior to a panel width of $1.2H$ where $H$ is the depth (Esterhuizen et al., 2010). This relationship was used rather than data from the mine because the data points along the panel width were sparse. The geometry used for this study is Mine C which has 400m wide panels 140m deep.
3.3.3 Young’s modulus

Esterhuizen and Karacan (2005) used a value of 1.25 Gpa for an Eastern US coal mine while Yavuz (2004), in a study of a Turkish coal mine, used 0.45 Gpa for Young’s modulus. In this study, cohesion and tensile strength were set to zero, the dilation angle was set to zero, Poisson’s ratio was set to 0.25 and the friction angle was 40 degrees. The value of Young’s modulus, was varied from 0.17 to 200 Gpa. Initial runs concluded that values below 170Mpa did not predict the supercritical behavior exhibited at the mines. The effect of Young’s modulus on surface subsidence is given in Figure 3.5. Over a large range, 0.17 – 200 Gpa, the surface subsidence profiles are similar and are within 0.3m of each other for maximum predicted subsidence. There is slight difference between the point at which the subsidence profile begins to flatten, higher values of Young’s modulus move the point further towards the center of the gob. A value of 8 Gpa predicted the location of the panel flattening the closest. The effect of Young’s modulus on gob compaction is given in Figure 3.6. Results show the value of Young’s modulus has little effect on gob compaction within the range of values tested.

The final models for Mine C and Mine E assign Young’s modulus as 8 Gpa for the Double Yield model.

![Figure 3.5: Impact of elastic modulus assignment on model prediction of surface subsidence](image-url)
3.3.4 Poisson’s ratio

A Poisson’s ratio of 0.04 was used by Esterhuizen and Karacan (2005). This value is low and will allow little transverse strain in the gob although due to confinement from the surrounding strata this is expected. In this present study, Poisson’s ratio was varied from 0.15 – 0.4. The remaining double yield model parameters are the same as for the calibration of Young’s modulus with the exception that Young’s modulus is 8 Gpa as previously determined.

The effect of Poisson’s ratio on surface subsidence is given in Figure 3.7 while its effect on gob compaction is given in Figure 3.8. Surface subsidence is only slightly affected by Poisson’s ratio. Gob compaction is even less sensitive. Additionally, the distance from the edge of the panel at which the subsidence profile begins to flatten is similar in all cases. The selection of Poisson’s ratio for the Double Yield model appears to only slightly affect the magnitude of subsidence and does not impact the shape of the subsidence profile. The model is not sensitive to these parameters since the gob is constrained on all sides by surrounding intact host rock.

Based on these sensitivity runs, final models for Mined C and E assigned a Poisson’s ratio of 0.25 for the Double Yield model.
Figure 3.7: Impact of Poisson’s ratio on model prediction of surface subsidence

Figure 3.8: Impact of Poisson’s ratio assignment on model prediction of displacement at the top of the gob
3.3.5 Friction and dilation angle

The angle of dilation controls the amount of plastic volumetric strain developed during plastic shearing. A value of zero corresponds to volume preservation during shear while a positive value corresponds to the volume reduction during shear. For non-cohesive soils with a friction angle greater than 30° the dilation angle can be estimated as the friction angle minus 30° (Bolton, 1986) and in most engineering applications the dilation angle can be assumed to be zero (Bolton, 1986). The amount of plastic volumetric strain during plastic shear deformation is controlled by the dilation angle. If dilation is considered, the material experiences plastic volumetric yield during plastic shear failure. This failure activates the strain hardening behavior of the Double Yield model and causes the material to ‘harden’ quicker, at lower levels of stress, than when dilation is not considered. Therefore the inclusion of dilation should cause lower levels of gob compaction and surface subsidence.

Since the dilation angle can be estimated from the friction angle, or zero, these two were evaluated together. A friction angle of 40 degrees was used by Esterhuizen and Karacan (2005) and 5 degrees by Yavuz (2004) for the gob. The dilation angle was not discussed by either authors and therefore is assumed to be zero since this is the default value assigned by FLAC$^3$D. For this study, the friction angle was varied from 30 – 40 degrees, with and without the dilation angle. Young’s Modulus and Poisson’s ratio were taken from the previously determined parametric studies and were assigned as 8 Gpa and 0.25, respectively.

The effect of friction angle and dilation angle on surface subsidence is shown in Figure 3.9. The dilation angle, when used, was assigned as the friction angle minus 30 degrees. In the figure, a dilation angle of zero is represented by a solid line whereas the dashed lines represent the response when a non-zero dilation angle was assigned. Subsidence was sensitive to both friction angles and dilation angles. Decreasing the friction angles increased maximum surface subsidence from 2.16m (45 degrees) to 2.6m (30 degrees). A higher friction angle also resulted in an increasingly flatter profile resembling supercritical behavior. When a value for the dilation angle was assigned, the magnitude of subsidence decreased due to the quicker hardening effect. This volumetric strain resulted in the strain hardening behavior activating at a lower stress and ultimately less subsidence. Subcritical behavior was exhibited with the inclusion of dilation angle. The prediction of gob compaction is given in Figure 3.10. The friction angle value did not impact the profiles but the larger values resulted in less gob compaction. Inclusion of
the dilation angle decreased the amount of gob compaction due to quicker activation of the hardening curve.

Figure 3.9: Impact of friction and dilation angle assignment on model prediction of surface subsidence

Figure 3.10: Impact of friction and dilation angle assignment on model prediction of displacement at top of gob
Assigning a friction angle of either 45° or 40° and a dilation angle of zero appeared to reproduce the measured subsidence profile. Due to the model’s sensitivity to these two parameters advice was obtained from a researcher at NIOSH (Esterhuizen, 2013). Based on this consultation, the final models for Mine C and Mine E used a friction angle of 40 degrees with a dilation angle of 0 degrees.

3.4 Model creation

This section covers the creation of the geomechanical model, introduces the concept of stepped extraction to simulate an active longwall mine and concludes with the validation of the geo-mechanical model.

3.4.1 Model set-up

The overburden for both models was represented using information provided by the mines. This included stratigraphic columns starting at the surface and extending down to a few feet below the coal, rock strengths and topography maps to help characterize the impact of elevation change on subsidence. The overburden was modeled using the Ubiquitous joint elements discussed previously. The rock parameters provided by Mine C are given in Table 3.3. The model did not capture each bedding layer but instead used a weighted average to determine the mechanical properties of each layer in the strata. The averaging was done only for rock types that were located within each vertical layer. The gob was modeled with the properties derived from the Double Yield model calibration effort.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Bulk Modulus Mpa</th>
<th>Shear Modulus Mpa</th>
<th>Density kg/m$^3$</th>
<th>Cohesion Mpa</th>
<th>Friction Angle Degrees</th>
<th>Dilation Angle Degrees</th>
<th>Tensile Strength Mpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>1,940</td>
<td>1,460</td>
<td>2,400</td>
<td>1.2</td>
<td>42</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Mudstone</td>
<td>850</td>
<td>510</td>
<td>2,380</td>
<td>0.4</td>
<td>38</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Shale</td>
<td>690</td>
<td>520</td>
<td>2,550</td>
<td>0.8</td>
<td>27</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Coal</td>
<td>580</td>
<td>440</td>
<td>1,330</td>
<td>0.42</td>
<td>48</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

Initially, each model consisted of cubic elements that were 10m in each dimension throughout the model. Refinement in the gob region was done after the initial calibration effort. Final grid size in the gob was elements that were 2.5mx2.5m and 10m high. This refinement was used based on a grid...
independence study. A further refined model replicating the geological sequence to include rock strata down to 2m showed insignificant difference since the rock properties were already averaged over the zone. A portion of the final Mine C model is shown in Figure 3.11. 15 grid layers were added below the coal seam and around the edges of the panel to ensure the gob did not experience any boundary effects. The number of layers required was determined in an iterative process using a smaller scale model. The boundary conditions for the model included fixing the floor to prevent displacement in all directions. Zero shear strength boundary conditions were applied to the sides of the model to simulate the confinement from surrounding strata.

Figure 3.11: Numerical model used for case study (Mine C). Top image depicts an isometric view. The next shows the gob and the boundary around the gob. The final shows the gob and face position.

3.4.2 Modeling stepped coal extraction of the longwall

If the entire longwall panel was extracted in a single step, the volumetric strain would be expected to be symmetric from start-up room to recovery room, giving an unrealistic representation of the mining process. If the coal is extracted in steps, modeling shows that such symmetry is no longer present,
leading to a more realistic representation of gob formation behavior. The stepped extraction process was completed by extracting one row of coal elements from headgate to tailgate in each step, assigning the elements with Double Yield behavior and running the model to convergence before the next extraction step. Figure 3.12 shows the difference between single-step and stepped extraction, where stepped extraction results in a sharp drop of the volume strain curve near the start-up room (x=0m) and a gentler rise near the recovery room (x =1000 m). There was numerical instability near the startup room of the model, evident near x=20m. This instability flattened out and this portion of the panel is irrelevant for researching the impact of near face ventilation hazards in the CFD model.

![Figure 3.12: Modeled method of extraction’s effect on gob compaction behavior (Mine C)](image)

The stepped extraction method produces a profile that is similar to that for a panel studied by Campoli (1993) who conducted a dynamic subsidence study of a longwall panel in a mine near Benton, IL. Gob compaction is directly related to surface subsidence, as the overburden sags and subsides increased loading is distributed to the gob material and compaction occurs. This process continues until the face has advanced a sufficient distance and the entire load of the overburden rests on the gob. The gob compacts under the increasing load and hardens until it resists further deformation. At this point the gob compaction remains constant as the face continues to advance towards the end of the panel. Near the face, the shields and the solid coal abutment provide partial support to the overburden and compaction is related to the distance inby the face. According to the Knothe time function, given in Equation (2.2, prediction of dynamic subsidence can be used to assess dynamic gob compaction since the two are directly related. The ratio between stepped extraction over single step extraction, is similar to the percentage of final subsidence from the Knothe time function. This percentage is plotted as a
function of distance inby the active face and is given in Figure 3.13. It is important to note the profile resembles exponential decay characteristic of the Knothe time function. A comparison of FLAC\textsuperscript{3D} results and subsidence data collected from surveying monuments oriented in the direction of face advance also shows close agreement as seen in Figure 3.14. Only Mine C data is shown since dynamic subsidence data was not available for Mine E.

![Ratio of Stepped to Single Step Gob Compaction](image)

Figure 3.13: Ratio of subsidence predictions from each extraction method (Mine C)

![Dynamic subsidence prediction compared to mine measurements](image)

Figure 3.14: Dynamic subsidence prediction compared to mine measurements (Mine C)
3.4.3 Model validation

Two separate compaction models were created using data provided by mines C and E. Subsidence measurements provided by the mines were used to validate each model. Mine C additionally provided dynamic subsidence data and shield loading data. The FLAC3D subsidence predictions for both mines are in close agreement with the field measurements conducted by the mines as shown in Figure 3.15.

A sensitivity analysis on panel width was completed for both models. When the panel width was decreased to 1.2 times the mining depth, the panel exhibited subcritical behavior. Shield loading data provided by Mine C was also used for verification of model predictions, as shown in Figure 3.16. This data confirms reasonable agreement between measured and calculated surface deformations and shield loads.

![Comparison of reported field subsidence measurements with model predictions](image)

Figure 3.15: Comparison of reported field subsidence measurements with model predictions (Mine C and E). Measurements taken across the width of the panel
Porosity and permeability determination

The porous media properties from the gob are determined through the Carman-Kozeny relationship for flow through porous media given by Equation (2.15. The output from the geomechanical model is volumetric strain or reduction in volume. The reduction in volume is assumed to be a direct reduction in the porosity of the unconsolidated gob. The porosity of the unconsolidated gob was determined from the bulking factor of the gob and the in-situ porosity of the immediate strata that caves into the gob. The volumetric strain predicted was subtracted from the porosity of the unconsolidated gob. The unconsolidated porosity in Mine C was 40%. This included a bulking factor of 33% and an initial porosity of the immediate mudstone and shale roof of 7%. The unconsolidated porosity in Mine E was 50%. This included a bulking factor of 33% and an initial porosity of the immediate sandstone roof of 17%. Once the porosity distribution was determined, the Carman-Kozeny relationship was used to determine permeability. A curve fit of volumetric strain was created as input data for the Fluent model. The conversion from volumetric strain to porosity and then permeability was computed inside a subroutine. This allows more transparency and flexibility for future researchers should another method for porous media conversion be considered in the future.

In Mine C, the porosity ranges from 40% to 14% while in Mine E, the porosity ranges from 50% to 32%. The porosity distributions are shown in Figure 3.17. The differences are primarily due to the host rock in the immediate roof which caves and forms the gob. In Mine C, the roof rock is a mixture of shale
and mudstone with a low initial porosity and a low resistance towards compaction. In Mine E, the roof rock consists of a massive sandstone with a high RQD that has a high bulking factor and a higher resistance to compaction. This has a direct impact on surface subsidence and porosity distribution. Mine C subsides 77% of the extracted seam height whereas Mine E only subsides 58% of the extracted seam height. The calculated permeability distributions are given in Figure 3.18. The values are plotted on a logarithmic scale. Mine C has a lower permeability than Mine E. The permeability ranged from $5.1 \times 10^{-6}$ to $2.0 \times 10^{-7}$ m$^2$ for Mine C and $6.9 \times 10^{-6}$ to $2.03 \times 10^{-6}$ m$^2$ for Mine E. These values are in reasonable agreement with values used by other researchers, as compared in Table 3.4. The differences in reported values are likely related to site specific geology, seam height, panel layouts and caving characteristics.
Table 3.4: Comparison of permeability findings from previous researchers (m$^2$)

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Max Permeability</th>
<th>Minimum Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m^2$</td>
<td>$m^2$</td>
</tr>
<tr>
<td>Szlazak (2001)</td>
<td>1.0x10^{-6}</td>
<td>5.10x10^{-9}</td>
</tr>
<tr>
<td>Esterhuizen and Karacan (2007)</td>
<td>1.0x10^{-6}</td>
<td>1.00x10^{-9}</td>
</tr>
<tr>
<td>Lolon (2009)</td>
<td>4.7x10^{-7}</td>
<td>8.10x10^{-9}</td>
</tr>
<tr>
<td>Karacan (2010) – High Bulking Factor</td>
<td>3.6x10^{-8}</td>
<td>1.50x10^{-8}</td>
</tr>
<tr>
<td>Karacan (2010) - Low Bulking Factor</td>
<td>1.3x10^{-8}</td>
<td>5.10x10^{-9}</td>
</tr>
<tr>
<td>Balusu (2011)</td>
<td>2.0x10^{-6}</td>
<td>2.00x10^{-9}</td>
</tr>
<tr>
<td>Mine C</td>
<td>5.1x10^{-6}</td>
<td>2.00x10^{-7}</td>
</tr>
<tr>
<td>Mine E</td>
<td>6.9x10^{-6}</td>
<td>2.00x10^{-6}</td>
</tr>
</tbody>
</table>

3.6 Conclusions of the geo-mechanical modeling

Reservoir properties of two longwall gobs were determined using FLAC$^{30}$. Information provided by the collaborating mines was used to validate the geotechnical models by comparing to site conditions. The models were created by using the Ubiquitous joint model for the overburden and the Double Yield model for the gob. A sensitivity analysis on parameters required for the Ubiquitous joint and Double Yield models revealed that the response was most sensitive to the strain hardening parameters. These strain hardening parameters were then calibrated against measured surface subsidence. The behavior of the model was verified against surface subsidence measurements and supercritical behavior. Data provided by Mine C also allowed validation against shield loading and dynamic subsidence measurement. Although beyond the scope of this dissertation, a subcritical trona mine gob was also modeled, using the same methodology presented above. This model also correctly predicted subcritical behavior.

‘Stepped extraction’ was shown to be more accurate compared to single step extraction for determining the response of active longwall coal mines. The porosity was calculated as the difference between initial gob porosity and the accumulated volumetric strain or of the gob compaction. Porosity for Mine C ranges from 40% around the edges of the gob and decreases to 14% near the center of the panel where compaction is highest. In Mine E, the porosity ranges from 50% to 32% and follows a similar spatial distribution. The resistance was determined from the porosity using the Carman-Kozeny equation for flow through porous media. The permeability ranges from 5.1x10^{-6} to 2.0x10^{-7} m$^2$ for Mine C and 6.9x10^{-6} to 2.0x10^{-6} m$^2$ for Mine E. The permeability is highest around the edges of the gob and lowest near the center.
CHAPTER 4
INTRODUCTION TO CFD AND MODELING ENVIRONMENT

This section provides details concerning the Computational Fluid Dynamics (CFD) modeling effort. The first section introduces CFD and describes the value in this application. This section also introduces the fundamental concepts of fluid flow and numerical methods implemented to allow computational solutions. The next section focuses on model creation, meshing and set-up. The final section introduces the algorithms used to obtain explosive gas volume results.

Fluid dynamics involves the study of fluids that are in motion and how the behavior of the fluid flow influences processes such as dissipation, diffusion, convection, boundary layers and turbulence. The governing flow physics are represented by a series of differential equations. For many flows of interest, these governing equations are nonlinear and therefore do not have an analytical solution. Computational fluid dynamics involves solving these nonlinear equations using iterative, numerical methods. Various types of numerical models have been developed for fluid flow, heat and mass transfer, chemical reactions and multi-phase flow. CFD can be used as a tool to gain insight and understanding of what governs physical events or processes that cannot be examined in a physical experiment.

CFD was first used for applications in the fields of aviation and aerospace. Since then it has been used in applications for automotive engineering, chemical and mineral processing, civil and environmental engineering, biomedical engineering, power generation and sports technology. Examples of CFD use in the field of mine ventilation include the study of air flow around continuous miners (Wala et, al 2008), refrigeration for hot mines (Greyling, 2011), controlling spontaneous combustion in longwall gobs (Yuan and Smith, 2007) and nitrogen inertization of both sealed and active panels (Balusu et, al 2005).

ANSYS Fluent, a commercially available CFD software package, was selected for this research. Fluent is well suited for this task because the model can be set up using either a Graphical User Interface (GUI) or Text User Interface (TUI). The GUI is straightforward, easily operated and can be used to quickly gain an understanding of the software’s capabilities. The TUI uses the same basic command structure as the GUI, and is required for running Fluent on a supercomputer. Fluent also allows users the flexibility to
write customizable subroutines, so-called user defined functions (UDFs), to modify model settings or boundary conditions and to create variables for post processing. Fluent has been used successfully by researchers at Commonwealth Scientific and Industrial Research Organization (CISRO) in Australia, and at the National Institute for Occupational Safety and Health (NIOSH) in the USA, as well as numerous other universities around the world for longwall gob ventilation research.

4.1 CFD constitutive equations

Most commercial CFD software, including ANSYS Fluent, uses the finite volume method to numerically solve the governing equations of fluid analysis. The fluid flow is defined by a set of equations stipulating the conservation of mass, momentum, species and energy. Turbulence can be defined by using one of several methods. This section presents the governing equations and describes the methodology used by Fluent to solve them.

4.1.1 Conservation equations

The governing equations for fluid flow, regardless of turbulence or chemical reactions, are based on the following physical laws: (1) mass is conserved in the system, (2) the rate of momentum change must equal the sum of the forces acting on the fluid and (3) the rate of energy change must equal the sum of heat transfer to or from the fluid and the rate of work done on or by the fluid. Conservation of total mass is ensured through the continuity equation. Conservation of mass also requires conservation of the individual chemical species mass, or species conservation, i.e., no matter can be created or destroyed. The Navier-Stokes equation ensures that momentum is conserved through Newton’s second law. The conservation of energy equation ensures thermodynamic equilibrium through the first law of thermodynamics.

The generic form of the conservation equations uses index notation, also known as subscript notation or tensor notation. This is a common method of representing the governing equations for fluid. A subscript i, j or k refers to the unit basis vectors, same as x, y and z. For clarity, the continuity equations and the momentum equations are given using index notation. The expanded versions do not use index notation. Further details regarding index notation and the full derivation of the Navier-Stokes equations can be found in Munson et al. (2012).
The conservation equations have the same generic form, as given in Equation (4.1). There are a total of four terms written in order as the local acceleration (unsteady) term, the advection term, the convection term and the source term. In generic form, the variable $\Phi$ is used to represent momentum, energy or species “k”. The diffusive coefficient, $\Gamma$, in the convection term and the source term, $S$, will change depending on the variable represented by the term $\Phi$.

$$\frac{\partial}{\partial t} (\rho \Phi) + \nabla \cdot (\rho \mathbf{u} \Phi) = \nabla \cdot (\Gamma \nabla) + S_{\Phi}$$  

Equation (4.1)

The continuity equation, given in Equation (4.2), states that the net mass flux entering the control volume must equal the net mass flux leaving the control volume, ensuring that the net change of mass inside the control volume is zero. Equation (4.3) gives the expanded version of the continuity equation.

The Navier-Stokes equation states that momentum is conserved within the control volume. Conservation of momentum in condensed form is given in Equation (4.4). The momentum is conserved by ensuring that the forces acting on the fluid result in a momentum change (sum of forces equals mass multiplied by acceleration). Any change in momentum requires that some force act on the fluid in the form of stress (axial or shear) times area or a body force. Body forces include gravity and are usually introduced through the source term. The expanded form includes one equation for the x, y and z directions as given respectively in Equations (4.5), (4.6) and (4.7). The source term, $S$, in the momentum equations, represents all body forces acting on the fluid. In many applications, gravity is the main body force acting on the fluid.

The conservation of energy equation is given in Equation (4.8). The rate of energy change in the system is governed by the second law of thermodynamics which states that the rate of change of energy in the system must equal work done on or by the fluid plus heat transferred to or from the fluid. Work done on the fluid is by means of the axial and shear viscous forces acting on the fluid. This work is converted into heat. Compressible flow includes a term for enthalpy. In incompressible flows, the enthalpy reduces to the specific heat of the fluid multiplied by the temperature difference. The source term in the energy equation has been replaced with the heat transfer rate, $\dot{q}$, since this is the only source term in most fluid dynamics problems.

In the absence of chemical reactions, which are not considered in the model, conservation of species states that molecules of species cannot be created nor destroyed. The conservation of species is ensured through the solution of a convection-diffusion equation for each species (ANSYS, 2013). The
conservation of species equation for non-reactive flow and minimal thermal gradients is presented by Equation (4.9. Since chemical reactions are not modeled, the source term, SY, or rate of addition (or subtraction) is only applicable to inlet or outlet boundary conditions. The convective term becomes an approximation of diffusive flux using Fick’s law, the default method in Fluent (ANSYS, 2013). The coefficient, \( D_{i,m} \), represents mass diffusion. Normally, a thermal diffusion coefficient (Soret coefficient) is also included in the approximation. Since, for this application, the thermal gradients are negligible, this term was not included.

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} \rho u_i = 0 \quad (4.2)
\]

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \quad (4.3)
\]

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ (v + v_T) \frac{\partial u_i}{\partial x_j} \right] + \left( -\frac{1}{\rho} \frac{\partial p}{\partial x_i} \right) \quad (4.4)
\]

\[
\frac{\partial \rho u}{\partial t} + \rho \left( \frac{\partial uu}{\partial x} + \frac{\partial vu}{\partial y} + \frac{\partial wu}{\partial z} \right) = \frac{\partial}{\partial x} \left[ (v + v_T) \frac{\partial u}{\partial x} \right] + \frac{\partial}{\partial y} \left[ (v + v_T) \frac{\partial u}{\partial y} \right] + \frac{\partial}{\partial z} \left[ (v + v_T) \frac{\partial u}{\partial z} \right] \quad (4.5)
\]

\[
\frac{\partial \rho v}{\partial t} + \rho \left( \frac{\partial uv}{\partial x} + \frac{\partial vv}{\partial y} + \frac{\partial wv}{\partial z} \right) = \frac{\partial}{\partial x} \left[ (v + v_T) \frac{\partial v}{\partial x} \right] + \frac{\partial}{\partial y} \left[ (v + v_T) \frac{\partial v}{\partial y} \right] + \frac{\partial}{\partial z} \left[ (v + v_T) \frac{\partial v}{\partial z} \right] \quad (4.6)
\]
\[
\frac{\partial \rho w}{\partial t} + \rho \left( \frac{\partial w u}{\partial x} + \frac{\partial w v}{\partial y} + \frac{\partial w w}{\partial z} \right) = \frac{\partial}{\partial z} \left[ (v + v_T) \frac{\partial w}{\partial x} \right] + \frac{\partial}{\partial y} \left[ (v + v_T) \frac{\partial w}{\partial y} \right] + \frac{\partial}{\partial z} \left[ (v + v_T) \frac{\partial w}{\partial z} \right] + \left( \frac{-1}{\rho} \frac{\partial p}{\partial z} + S_w \right)
\]

\[
\frac{\partial T}{\partial t} + \frac{\partial u_j T}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \frac{v}{P + PR} + \frac{v_T}{PR_T} \right) \frac{\partial T}{\partial x_j} \right] + \dot{q}
\]

\[
\frac{\partial \rho Y_i}{\partial t} + \frac{\partial u_j \rho Y_k}{\partial x_j} = \rho \frac{\partial D_k Y_k}{\partial x_j} J_k + S_Y
\]

### 4.1.2 Equation of state

The equation of state is presented in Equation (4.10. The ideal gas law was chosen since pressure and temperature do not change significantly enough to affect the validity of the ideal gas law.

\[
p = \rho RT
\]

### 4.1.3 Porous media formulation

The porous media model, used in the gob and fractured zone, adds an additional source term to the Navier Stokes (momentum) equation to account for the energy loss. This source term is given in Equation (4.11. The laminar portion of the source term is Darcy’s law. The turbulent portion includes an inertial resistance coefficient, \( C_d \), which is determined using the Ergun equation (Ergun, 1949). The Ergun equation uses the friction factor across a packed bed and the flow’s Reynold’s number to determine a pressure drop (ANSYS, 2013).
Evaluation of the Reynolds number is a means of determining whether a flow is laminar or turbulent. The Reynolds number, \( Re = \frac{\rho v D_h}{\mu} \), is a function of density, dynamic viscosity, mean flow speed and hydraulic diameter. As the Reynolds number increases above 2,300, the flow becomes unstable, or turbulent. Turbulence can be characterized as chaotic motion of swirls and eddies with large velocity fluctuations which induce additional stresses in the form of convective acceleration in the fluid flow. These stresses are known as Reynolds stresses. Resolving the specific details of the turbulent fluctuations for each eddy is not practical so numerical models have been developed to approximate turbulence. Most turbulence models work on the principle of mean flow. A technique known as Reynolds-averaged Navier-Stokes (RANS) was developed by applying Reynolds decomposition to obtain the mean flow characteristics and remove the time dependence of turbulence (Reynolds, 1883). Reynolds decomposition defines the fluid in terms of mean velocity and intensity of the turbulent fluctuations. This approach results in a closure problem or more unknown variables that equations to solve for the unknown variables. One way of addressing the closure problem is through the Boussinesq approximation (Boussinesq, 1868), i.e., by assuming the Reynold’s stresses can be linked to the mean rates of deformation or turbulent fluctuation. According to the Fluent manual, the Boussinesq hypothesis is sufficient and the additional computational expense of the Reynolds stress model is not justified (ANSYS, 2013). A number of other turbulent models exist however none are universally accepted as superior for all types of flows (ANSYS, 2013).

The k-\( \varepsilon \) turbulence model is a two-equation Reynolds’ stress transport model. The two parameters are turbulent kinetic energy (\( k \)) and turbulent dissipation (\( \varepsilon \)). This model is frequently used for engineering flow calculations due to its robustness, fast solution times, and accuracy over a wide range of flows. Experiments by Bardina et. al. (1997) have shown the k-\( \varepsilon \) model performs well in free-shear layer flows, such as jets or nozzles and for wall-bounded or internal flows as long as the pressure gradients are small. FLUENT offers three variations of the k-\( \varepsilon \) model: the standard, RNG, and Realizable variations.
The standard k-ε model is a semi-empirical model derived from transport equations and empirical constants. It adds two additional equations solving for k and ε to define turbulent viscosity, which, in turn is added to a fluid’s laminar viscosity in the energy and momentum equations. Important assumptions in the derivation of this variant include that the flow is fully turbulent and molecular viscosity is negligible. The rate of change and the advection transport of k or ε equals the diffusion transport combined with the rate of production and destruction of k or ε. One primary disadvantage of this model is that, in highly strained flows, the production of turbulence is over predicted.

The RNG (Re-Normalization Group) k-ε theory was developed by Choudhury (1993). The RNG method statistically re-normalizes the Navier Stokes equations. The RNG model includes an analytical formula for turbulent Prandtl numbers and an analytically derived differential for effective viscosity. The differential allows the turbulence model to account for lower Reynolds number flows involving several smaller scales of motion rather than one large scale of motion dominating the flow and therefore the turbulent length scale. In the longwall gob model, the flow inside the gob is much slower (lower Reynolds number) than flow within the face and void areas of the mine. The implementation of the differential viscosity allows for better prediction of laminar flow and transitional flow regimes within the gob. The RNG k-ε method was used for this research for the following reasons: The majority of the model (gob) contains low Reynolds number flow and the area directly behind the longwall shields, which was of most interest, transitioned quickly from a high to a low Reynolds number flow. Further, an extensive study by Worrall (2012) comparing the standard k-ε model to the RNG k-ε model determined that the standard k-ε model did not perform as well. The transport equations for the RNG k-ε turbulence model are given in Equation (4.12) and (4.13) using index notation.

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M \tag{4.12}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left( \alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \tag{4.13}
\]
The terms in the k-ε RNG transport equations are defined by ANSYS (2013) as follows:

- The term $G_k$ is the generation of $k$ from the mean velocity gradients and is calculated using the following relationship: $G_k = \mu_k S^2$. The term $\mu_k$ represents turbulent viscosity and the term $S$ is the modulus of the mean rate of strain tensor defined as $S = \sqrt{2S_{ij}S_{ij}}$.

- The term $G_b$ is the generation of $k$ from buoyancy effects (important when gravity is modeled) and for ideal gases is calculated using the following relationship: $G_b = -\frac{g_i \mu_t}{\rho Pr_t} \frac{\partial \rho}{\partial x_i}$. The term $g_i$ is the gravitational constant in the $i^{th}$ direction and $Pr_t$ is the turbulent Prandtl number defined as $Pr_t = 1/\alpha_T$ where alpha is the inverse turbulent Prandtl number. The inverse turbulent Prandtl number is derived analytically from RNG theory as given in Equation (4.14 where $\alpha_0$ is the inverse Prandtl number (laminar). This same equation is also used to derive the inverse effective turbulent Prandtl numbers for kinetic energy transport, $\alpha_k$, and for turbulent dissipation transport, $\alpha_\varepsilon$. The difference is the value of $\alpha_0$ becomes 1.0 for inverse effective Prandtl number calculations. In Equation 4.8a $\alpha_T$ is the inverse turbulent Prandtl number. The subscript changes to represent $\alpha_k$ or $\alpha_\varepsilon$ so long as the appropriate changes are made to $\alpha_0$. The term $\mu$ represents molecular viscosity and effective viscosity is defined as $\mu_{eff} = \mu \hat{b}$ where $\hat{b}$ is the turbulent viscosity ratio.

- The dilation dissipation term, $Y_M$, accounts for the compressibility effects through a phenomenon known as dilation dissipation. Dilation dissipation is observed through decreased spreading rate with increased Mach numbers for compressible mixing and other free shear layers. This phenomenon only occurs in compressible flow, not in the incompressible ideal gas which is modeled. Therefore this term is set to zero.

- The term $C_{2\varepsilon}$ is an empirically derived correction for to better capture the destruction of $\varepsilon$ in highly strained flows. The correction factor is calculated according to Equation 4.8b where $\eta$ represents the modulus of the mean rate of strain tensor, $S$ (defined previously), multiplied by the ratio of turbulent kinetic energy to turbulent dissipation as shown: $\eta = S \frac{k}{\varepsilon}$. The remaining variables in Equation 4.8b are empirically derived constants.

- The term $C_{3\varepsilon}$ is used to influence the impact of buoyancy on the turbulent dissipation, an effect which is not well understood. In Fluent this term is calculation using a relationship proposed by Henkes et. al. (1992): $C_{3\varepsilon} = \tanh \left| \frac{w}{u} \right|$ where $w$ is the component of velocity parallel to gravity and $u$ is the component of gravity perpendicular to gravity.

- The remaining terms are model constants derived analytically from RNG theory (Choudhury, 1993) and are given in Table 4.1.
\[
\left(\frac{\alpha_T - 1.3929}{\alpha_0 - 1.3929}\right)^{0.6321} \left(\frac{\alpha_T + 2.3929}{\alpha_0 + 2.3929}\right)^{0.3679} = \frac{\mu}{\mu_{eff}}
\] (4.14)

\[
C_{2e} = C_{2e} + \frac{C_{\mu} \eta^3 \left(1 - \frac{\eta}{\eta_0}\right)}{1 + \beta \eta^3}
\] (4.15)

Table 4.1: Analytically derived constants for the k-\(\epsilon\) RNG turbulence model by Choudhury (1993)

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta_0)</td>
<td>4.38</td>
</tr>
<tr>
<td>(\beta)</td>
<td>0.012</td>
</tr>
<tr>
<td>(C_{1\epsilon})</td>
<td>1.42</td>
</tr>
<tr>
<td>(C_{2\epsilon})</td>
<td>1.68</td>
</tr>
</tbody>
</table>

4.2 Problem solving in FLUENT

The process of solving problems in FLUENT involves six basic steps. The first step is to specify the geometry of the problem, the computational domain. The geometry should incorporate all major features of the environment but should neglect minor features that are not expected to impact the final results. The second step is the creation of a mesh which divides the domain into a series of finite volumes in order to establish the differential equations governing the fluid flow into a form solvable on a computer. The accuracy of the solution is highly dependent on the quality of the mesh. The third step defines the fluid and material properties that must be modeled and assigns the physical processes that are of interest. The assignment of physical processes requires fully identifying the governing flow physics of the problem. For example, the model must specify whether the problem is time-dependent (transient) or steady state, whether the flow is laminar or turbulent, whether the fluid is viscous or inviscid, whether the assumption of incompressible flow can be made, whether there is significant heat transfer, and whether chemical reactions need to be modeled. The fourth step defines and applies boundary conditions to the model. Boundary conditions should be specified at locations where parameters are known or where verification measurements can be taken. If measurements are not possible, reasonable assumptions must be formulated in a manner that incorporates as much known information as possible. For inlets and outlets, the entry length must be sufficient to ensure the flow is fully developed before it enters or exits the zone of interest. The fifth step defines the solver settings.
and the numerical schemes that will be used to solve the problem. The final step involves solving the model. The solution step is broken into two segments, solution initialization and solution iteration. In the initialization step the solution is initialized using boundary interpolation methods and Laplace’s equation is used to determine the initial velocity and pressure fields (ANSYS, 2013). In the iteration step, the equations are solved in an iterative fashion until a converged solution is reached. The results can be post processed for graphical display purposes.

4.2.1 Finite volume discretization

In ANSYS Fluent the transport conservation equations are solved using the finite volume discretization approach. This approach converts the original partial differential equations into a series of algebraic equations discretized in order to yield values at discrete locations and times.

The discretization scheme uses the generic differential form of the conservation equations given in Equation (4.1. Integrating the conservation equation over the finite volume (control volume) and applying the Gauss Divergence theorem yields the generic integral form of the conservation equations given in Equation (4.16. The finite volume approach discretizes the domain into a finite number of control volumes, the mesh. An example 2-D mesh is depicted in Figure 4.1 as a visual aid for this explanation. At the center of each control volume, the value of the dependent variable $\Phi$ is calculated and this value is linearly interpolated onto the surfaces of the control volume. This approach allows for approximation of the surface and volume integrals. The principle of the approach is to convert the differential form of the transport equations into algebraic equations. This is accomplished through control volume integration and the Gauss divergence theorem. The surface areas are resolved along the Cartesian coordinate directions resulting in the projected areas $A_1 – A_4$, see Figure 4.1. The normal vector of each surface determines whether the area of that surface should be assigned a positive or negative flux. The convention is positive flux if it is in the same direction as the principal Cartesian coordinate system vectors; otherwise the flux is negative.

The finite volume discretization is similar for first and second order differentials. The method is to first apply control volume integration and then to apply the Gauss divergence theorem. This is shown for first order (Equation (4.17) and second order (Equation (4.18) differentials in the x direction (exact same concept for y and z direction). In the second order differential approximation, a first order differential remains and must be evaluated at the face of the cell. This is usually done with a simple linear gradient.
calculation between the central node and surrounding nodes (first order upwind). Using this process, the governing equations are converted into a system of algebraic equations and solved numerically.

\[
\frac{\partial}{\partial t} \int_V \rho \Phi \, dV + \oint_A \rho u \Phi \cdot dA = \oint_A \Gamma_{\Phi} \nabla_i \cdot dA + \int_V S_\Phi \, dV
\]

\[
\frac{\partial \Phi}{\partial x} = \frac{1}{\Delta V} \oint_A \Phi \, dA_x \approx \frac{1}{\Delta V} \sum_{i=1}^{N} \Phi_i A_i^x
\]

\[
\frac{\partial^2 \Phi}{\partial x^2} = \frac{1}{\Delta V} \oint_A \frac{\partial \Phi}{\partial x} \, dA_x \approx \frac{1}{\Delta V} \sum_{i=1}^{N} \left( \frac{\partial \Phi}{\partial x} \right)_i A_i^x
\]

4.2.2 Iterative process

Once the differential transport equations have been converted into a system of algebraic equations, an iterative technique is used to reach a solution. The iterative process is continued until the solution converges to the user specified criteria. The criteria used to govern convergence is a residual defined as an imbalance in the conservation equations. Most problems require that the normalized residuals converge to $1 \times 10^{-3}$; in more complex flow fields even lower. The convergence criterion used for this research was $1 \times 10^{-4}$ for all variables with the exception of continuity, which was set at $5 \times 10^{-4}$, and energy, which was set at $1 \times 10^{-6}$.
A brief overview of the iterative process is useful for explaining the concept of a residual. After
discretization, similar terms can be collected and the conservation equation for the general variable \( \Phi \) can be re-written. The result resembles the general form of Equation (4.19 where the subscript “\( nb \)” refers to neighboring cells and the subscript \( p \) refers to the value at cell \( p \). The coefficient \( a \) represents the influence coefficients (dependent on the conservation variable \( \Phi \)) and the variable \( b \), represents the contribution from boundary conditions and the constant part of the source term (ANSYS, 2013). The residual calculation method differs slightly depending on the solver type that is used. Only the pressure-based solver was used, so this method will be discussed. The residual term, \( R_\Phi \), is the imbalance in Equation (4.20 summed over all of the cells within the computational domain. To aid the user in determination of convergence the residual value is globally scaled as shown in Equation (4.21. Global scaling, as used in this research, means the residual is scaled over the entire domain rather than local scaling over a smaller, specified domain. This method of determining the residuals is valid for all conservation equations with the exception of the continuity equation. The residual of the continuity equation is the mass imbalance within the cell. The globally scaled continuity residual is defined as the current mass imbalance (residual) divided by the largest continuity residual from the first five iterations.

\[
a_p \Phi_p = \sum a_{nb} \Phi_{nb} + b_S \tag{4.19}
\]

\[
R_\Phi = \frac{\sum_{Cells,p} \sum_{nb} a_{nb} \Phi_{nb} + b_S - a_p \Phi_p}{\sum_{Cells,p} |a_p \Phi_p|} \tag{4.20}
\]

Fluent implements under-relaxation factors to improve stability due to the nonlinearity of the
equations. The under-relaxation factors reduce the amount of change the conservation variable can
make from one iteration to the next. The implementation of the under-relaxation factor is shown in
Equation 4.15 where \( \alpha \) is the under-relaxation factor and is less than unity.

\[
\Phi_{p,Actual} = \Phi_{Old} + \alpha \Delta \Phi_{Calculated-Old} \tag{4.21}
\]
The finite difference method is built on the basis of dividing the computational domain into finite volumes. Each volume is bounded by nodes. Each node is usually shared by more than one volume. This arrangement of finite volumes and nodes is referred to as the computational mesh. The accuracy, stability and computational speed is largely dependent on the quality of the mesh. Generally, the smaller the volume enclosed by each cell, the more accurate the solution, but the larger the computation time. The expected flow type is one of the driving factors in determining an appropriate mesh size. Mesh refinement is used in areas where a finer mesh is required for a given flow while the majority of the domain can be solved to sufficient accuracy with a larger mesh. One example is the gob flow model which requires refinement to a size of 2.8E-05m$^3$ in fast flowing, turbulent regions. In the center of the gob, flow is on the order of centimeters per day and can be solved using rather large grid cells (up to 116m$^3$).

Size is not the only important metric in determining mesh quality. The quality of a mesh is measured in Fluent using several metrics including cell quality, skewness, aspect ratio, and relative size change. The most important metrics are cell quality and skewness. Fluent defines cell quality as how close the cell shape is to the ideal shape, that of an equilateral tetrahedron or hexahedron with the same circumradius. The equation Fluent uses to calculate the cell quality is given in Equation (4.22). ANSYS Fluent recommends a minimum cell quality across the whole domain be greater than 0.01 with the average cell quality significantly higher. Fluent defines skewness as the difference between the shape of the cell and the shape of an equilateral cell with the same volume. The equation Fluent uses to calculate cell skewness is given in Equation (4.23. The variables are defined as follows: $q_e$ is the angle for an equiangular face or cell; 60° for a triangle and 90° for a square), $q_{min}$ is the smallest angle in the face or cell and $q_{max}$ is the largest angle in the face or cell.

\[
\text{Cell Quality} = \left| \frac{\text{Optimal Volume} - \text{Cell Volume}}{\text{Optimal Volume}} \right| \quad (4.22)
\]

\[
\text{Skewness} = \max \left[ \frac{q_{max} - q_e}{180 - q_e} \quad \text{or} \quad \frac{q_e - q_{min}}{q_e} \right] \quad (4.23)
\]
Fluent recommends that the maximum skewness across the domain be less than 0.95 with average values significantly lower. If these conditions are not met, the user may experience slow or unstable convergence or even divergence. In general, lower skewness and higher cell quality models are faster to solve and are more stable.

The type of grid element shape used to discretize the computational domain is also important. The two dominant types are hexahedral and tetrahedral. According to ANSYS (2013), hexahedral elements are better suited in areas of laminar flow. Hexahedral elements solve more quickly and should be used wherever possible. In areas of turbulent flow, hexahedral elements may perform poorly and tetrahedral elements should be used.

Achieving a high quality mesh is often one of the most time-consuming processes associated with CFD problems (Tu et al., 2007). In complex problems such as longwall gob modeling, this task can take weeks or months. The common approach is to mesh the entire domain in one pass and this is the default mesh creation setting in Fluent. This approach does not lend itself well to parametric studies that require different geometries to be used. A more productive approach is to re-use the same mesh elements as often as possible. A modular meshing technique developed by Gilmore (2014) was used to develop variable meshes with consistent and high quality.

A flow chart for the modular meshing technique is presented in Figure 4.2. The first step is the creation of a new geometry module, which requires meshing. Using the modular technique, only new geometry modules need to be re-meshed. The new geometry module can then be stored in a library and these modules can be used to assemble a wide range of model geometries. This meshing approach is flexible. When a geometry or ventilation control change is required, it can be created using pre-existing modules. This method can also be used to study a wide range of geometries by modifying the dimensions of the modules. A module that needs to be updated can be replaced with a new or existing module to fit the required need. A depiction of the final mesh from a bleeder ventilated longwall gob model is depicted in Figure 4.3. Despite the complexity of a full bleeder ventilated longwall CFD model, the mesh was created using only nine modular pieces.
4.2.4 Solver settings

ANSYS Fluent offers a number of theoretical packages and numerical schemes to aid convergence of CFD problems. The solver settings used for this research are given in Table 4.2. The flow was assumed to be incompressible, implying the density remains constant not that the fluid itself is incompressible. This assumption is possible due to the small pressure variations over the modeling domain. This allows for a pressure based solver to be used. The absolute velocity formulation is acceptable for low velocity flows. The solver was steady state, although some research topics involved studying the transient effects of nitrogen injection in the gob. Modeling gravity lead to instability (divergence) due to the buoyancy effects once it was turned on. Numerous attempts were made to get gravity runs to converge. Attempts including reducing the relaxation factors for both pressure and momentum, switching the pressure scheme to body-weighted forces, turning on gravity incrementally and reducing all relaxation factors. A
discussion with Liming Yuan, a CFD gob researcher at NIOSH, revealed that NIOSH had the same issues and decided to neglect gravity. The results particularly in low flow regions of the gob and at height maybe impacted once gravity is turned on. The majority of the flow in the gob is controlled by inertial forces which are orders of magnitude larger than the buoyancy forces present. Worrall (2012) determined the magnitude of gravity effects was five times smaller than the magnitude of the inertial forces. It may be possible to capture the effects of gravity if the mesh is sufficiently refined. Instability occurred in the turbulent residuals for both $k$ and $\epsilon$ when gravity was turned on. This suggests that the turbulent effects of gravity cannot be resolved with the mesh size currently in use. An attempt using 0.3 meter cells throughout the model did not result in convergence. Smaller mesh sizes violate one of the fundamental assumptions of the porous media model. The mesh size must not be smaller than the largest void in the gob. This research assumed 0.2 meters from the work done by Pappas and Mark (1993) and Esterhuizen and Karacan (2005). The formulation of the porous media model by Ansys requires that the control volumes created by the mesh must, at a minimum, include one complete void. If the mesh is smaller than the largest void, the control volume enclosed by the void would be subject to free flow invalidating the assumptions made in the porous media model. The only work around for this issue is to create a model with geometry that captures the voids and interconnecting channels. This would require understanding of the actual geometry of the gob, something which cannot be determined using currently available technology. For these reasons gravity was not modeled during this research.

Table 4.2: Fluent General Settings

<table>
<thead>
<tr>
<th>ANSYS Fluent®</th>
<th>Solver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>Incompressible Ideal Gas</td>
</tr>
<tr>
<td>Type</td>
<td>Pressure-Based</td>
</tr>
<tr>
<td>Velocity Formulation</td>
<td>Absolute</td>
</tr>
<tr>
<td>Time</td>
<td>Steady</td>
</tr>
<tr>
<td>Gravity</td>
<td>off</td>
</tr>
</tbody>
</table>

An extensive study of model settings for using Fluent to study gob gas flows was completed by Worrall (2012). The porous media model is based on the geo-mechanical analysis and was turned on for the gob and the strata. Differences that exist from Worrall’s setup include turning each equation on individually and iterating until the solution has converged before turning on the next equation. This was found to make the model more stable as opposed to starting from the initialization step having a nitrogen atmosphere throughout the entire domain and solving all of the flow equations simultaneously.
The order in which the conservation equations were turned on is as follows. First, continuity and momentum were turned on, then energy, turbulence and finally, species conservation. All equations were solved using a first order discretization scheme for neighboring cells only. Once the solution was nearly converged, second order discretization involving two levels of neighboring cells was used for gas species. The model variations used during this research are summarized in Table 4.3. Numerical schemes implemented in this research are summarized in Table 4.4.

Table 4.3: Fluent Model Settings

<table>
<thead>
<tr>
<th>ANSYS Fluent®</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>On</td>
</tr>
<tr>
<td>Viscous</td>
<td>RNG k-ε, Standard Wall Function, Differential Viscosity Model</td>
</tr>
<tr>
<td>Species Transport</td>
<td>CH₄, O₂, N₂</td>
</tr>
<tr>
<td>Porous Media Model</td>
<td>Gob and Strata</td>
</tr>
</tbody>
</table>

Table 4.4: Fluent Solution methods and controls settings

<table>
<thead>
<tr>
<th>ANSYS Fluent®</th>
<th>Solution Method or Discretization Scheme</th>
<th>Under-Relaxation Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure-Velocity Coupling</td>
<td>SIMPLE</td>
<td>n/a</td>
</tr>
<tr>
<td>Gradient</td>
<td>Least Squares Cell Based</td>
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<tr>
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</tr>
<tr>
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<tr>
<td>Turbulent Kinetic Energy</td>
<td>1st Order Upwind</td>
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</tr>
<tr>
<td>Turbulent Dissipation Rate</td>
<td>1st Order Upwind</td>
<td>0.7</td>
</tr>
<tr>
<td>Species</td>
<td>2nd Order Upwind</td>
<td>1</td>
</tr>
<tr>
<td>Energy</td>
<td>1st Order Upwind</td>
<td>1</td>
</tr>
</tbody>
</table>

The default pressure-velocity coupling scheme is SIMPLE. This was the scheme used for all runs within this research. PISO is recommended by ANSYS for transient runs that require large time steps although no issues were encountered while using the SIMPLE scheme and initial time steps were on the order of a few seconds. Steady-state runs that attempted to use PISO resulted in divergence so this scheme was not used.
The default pressure gradient interpolation ANSYS offers is the Least-Squares Gradient method. This method was used since it is the least computationally expensive and performs well using structured meshes. It involves linearly interpolating the value at the center of the cell to the cell faces. The gradients are also required for solving the secondary diffusion terms and velocity derivatives.

The default pressure interpolation scheme offered by ANSYS is SIMPLE. PRESTO! was used because it is recommended by ANSYS for porous media flow.

The default discretization scheme offered by ANSYS Fluent is 1st order upwind. This scheme involves interpolating the gradients using only the first layer of surrounding cells. The 2nd order upwind scheme involves using the first two layers of surrounding cells for the interpolation. This method was used for species due to the convective nature of gas dilution.

4.2.5 Post processing algorithms

Fluent allows the user to implement subroutines to define variables for use in post-processing. The code is compiled inside of FLUENT in the form of a user-defined function (UDF). Worrall et al., (2012) developed an explosive gas algorithm that color codes methane-air explosibility based on Coward’s Triangle (Coward and Jones, 1952) and concentrations of methane and oxygen predicted by the model. The UDF also calculates the volume of the UDF.

The explosive potential for mixtures of methane and air is presented using the coloring scheme depicted in Figure 4.4. There are six distinct regions: the explosive region in red, an arbitrary, near-explosive region colored orange, a fuel-rich inert region that can become explosive when fresh air or oxygen is added, colored yellow, an inert region where no explosive composition is possible, in (green, an inert region with insufficient fuel or fuel-lean inert, in blue, also representing fresh air, and a nitrogen-rich inert region in dark green,. This coloring scheme will be used as a legend for all explosive gas zone (EGZ) figures presented throughout. The formulation of this UDF is given in Appendix B.

Additional post processing tools include contour plots, vector plots, 3-D iso-surfaces and reports. Contour plots, unless otherwise noted, are presented in plan view of the mine, using a plane at a height of 1.5m above the mine floor, roughly the middle of the coal seam height. Although other regions of the gob are also important, this plane is used to depict EGZ hazards that may affect the miners.
Figure 4.4: Coward’s triangle. Color coded to depict EGZ zones on contour plots. This is to be used as a legend for all EGZ plots. Modified from the original by Coward (1952)

4.3 Model description and validation

This section presents the geometry, boundary conditions used throughout the CFD gob models and the model validation process. Portions of two peer reviewed conference papers are incorporated in this section. One was published in the September issue of the 2013 Journal of Mining Engineering (Marts 2013) the other published in the proceedings of the 4th Annual Aachen International Mining Symposia (Marts 2014).

Cooperating mines C and E shared data for model creation and validation. Both mines implement tube bundle gas monitoring systems and U-Type ventilation in conjunction with progressive nitrogen injection. The mine geometry was represented from mine maps and visual observations made during mine visits. Mine ventilation plans included information regarding face ventilation quantity, typical nitrogen injection details (locations and rates) and gob vent borehole operating conditions (gob vent boreholes used at Mine C only). This data was used to specify the boundary conditions of the CFD model. Validation data included gas concentration measurements from the installed tube bundle system, gob vent boreholes and other atmospheric monitoring devices. Several visits were made to the
partner mine sites to share findings and discuss validation. Ventilation engineers from each site reviewed the modeling strategy and findings. These visits and examinations concluded that the model represented reality with sufficient accuracy for trend analysis. Mine C used the CFD studies to verify their own CFD findings. Mine E outcrops on all sides and the tube bundle readings show only trace amounts of methane. The primary gob gas at Mine E is carbon dioxide which is generated as a result of coal oxidation. Oxidation and spontaneous combustion are considered outside the scope of this dissertation work. The oxygen ingress is discussed but modeling the chemical reactions was not attempted.

4.3.1 Longwall panel geometry and boundary conditions

The CFD model represents the geometry and stratigraphy of Mine C. The full panel width was modeled as 310m. The height of the gob and that of the fractured zone, the region above the gob, were determined from information provided by Mine C: a gob height of 13m and a fractured zone height of 24m. A rider coal seam was modeled above the fractured zone and is the source of methane in the model. The entire panel length was not modeled based on earlier studies by Worrall (2012) that showed the entire length of the gob does not need to be modeled when studying near-face gas distributions in progressively sealed longwall panels. Worrall’s study showed no significant change from a partial length model to a full length model if the partial model was at least 500m long. The reduced model length was about 900m to allow studying nitrogen injection locations inby the face. Two gob vent boreholes (GVBs) are included in the model. The gob vent boreholes are terminated 18m above the mine floor, 18m from the tailgate gate roads and distances of 66m and 133m, respectively, inby the face. In initial studies, nitrogen was injected through the first two inby crosscuts on the headgate side and through the first inby crosscut on the tailgate side, corresponding to actual injection locations at the mine. A depiction of the model in plan view is shown in Figure 4.5.

In the CFD models, a geometric replication of a typical longwall support shield was used for the face mesh module. This is a significant advancement in the area of longwall gob gas research that previously had not been accomplished. A study by Ren and Wang (2013) involved a face model using actual longwall shields, although the purpose was for dust particle tracking only and a gob model was not included. Previous researchers have used wide open airways with leakage openings (Worrall, 2012) or a porous jump which simulates a pressure drop across a face or zone (Yuan and Smith, 2014). These simplifications were required due to the complexities involved in meshing the entire computational
domain at once. The longwall face model would not have been achievable without the development of the modular meshing technique (Gilmore, 2014). The importance of the longwall face model is that turbulence caused by the shields was determined to have a significant effect on air ingress into the gob and the resulting gas distributions. A depiction of the longwall shield mesh used for this research is given in Figure 4.6.

Figure 4.5: Plan view of the CFD gob model (not to scale)

Figure 4.6: Depiction of the longwall shield mesh use in the face model (Gilmore, 2014; not to scale)
The following boundary conditions were used in the model:

- Intake air across the face: 33m$^3$/s of fresh air (20.9% $O_2$)
- Pressure drop across the face: 78.0 Pa
- Porous media properties: Determined from $FLAC^3D$ modeling
- Headgate 1$^{st}$ crosscut nitrogen injection rate: 0.095m$^3$/s
- Headgate 2$^{nd}$ crosscut nitrogen injection rate: 0.095m$^3$/s
- Tailgate nitrogen injection rate: 0.19m$^3$/s
- Gob vent borehole flow rates: 0.17m$^3$/s each
- Gob vent borehole % CH$_4$: $\geq$ 95%
- Tailgate return % CH$_4$: < 0.5%
- Tailgate return Pressure outlet
- Methane inlet rate: 0.5m$^3$/s

4.3.2 Model validation

Numerous variables must be considered for gob modeling. Many variables cannot be measured directly which contributes to the difficulty of gob modeling. Simplifications applied to the model include assuming that the face is stationary, the barometric pressure remains constant and the oxidation reactions between coal and oxygen are negligible. The amount of methane liberation is back calculated from mine examination data in order for the model to approximate actual gas distributions inside the gob.

Model validation was achieved by changing the amount of methane released into the model until the model predictions matched the known boundary conditions. The Fluent User’s Guide (ANSYS, 2013) provided guidance on the assignment of flow physics. Fluent recommends several strategies depending on both the type of problem and type of flow. The validation process in combination with the guidance from Fluent regarding flow physics and boundary condition assignment ensured fidelity to known operating conditions. Additionally, the results were examined to ensure reasonable flow behavior. Validation points included flow quantity and methane mole fraction in the tailgate return, methane mole fraction and flow rates in the gob vent boreholes and tube bundle gas concentration from several locations. The final conditions were verified with mine personnel to confirm reasonable assumptions for the base model. The model corresponds well to field measurements of gas concentrations taken around the fringes of the gob. The methane concentration in the tailgate return can fluctuate; with concentrations remaining below the statutory threshold of 1.0%.
The results of the model also agree with operator experience. This is summarized below:

- The methane concentration at the tailgate return matched Mine C measurements.
- The methane concentration at the gob vent boreholes matched Mine C measurements.
- Methane enters the face primarily at the tailgate corner.
- Low oxygen exists behind the shields inby the tailgate corner.
- Tube bundle measurements: headgate (>90% nitrogen) and tailgate (>90% methane)

![Figure 4.7: Comparison of nitrogen contour predictions to model by Yuan and Smith (2014)](image)

Additional validation was made through comparison with published research results. Yuan and Smith (2014) studied the effectiveness of nitrogen injection into a longwall gob for the purpose of mitigating spontaneous combustion. In their model, the face ventilation quantity was 30.5m3/s with nitrogen injected through the first headgate crosscuts at a rate of 0.19m3/s. The gob porosity distributions in both models are similar $3 \times 10^{-6} - 8.5 \times 10^{-6}$ x10-6m2 (Yuan and Smith, 2014) compared to $5.1 \times 10^{-6}$ to $2.0 \times 10^{-7}$m2 or the Mine C model shown on the left. Figure 4.7 shows a comparison between Yuan and Smith’s (2014) model (left) and the model used for the current research (right). In the Yuan and Smith model the nitrogen is injected at a rate of 0.19m3/s where noted. In the current model the nitrogen is injected at 0.095m3/s from each of the first two headgate crosscuts at a rate of and 0.19m3/s from the tailgate crosscut. The only difference between the two models is the single nitrogen injection location in Yuan and Smith, (2014) as opposed to the dual injection. Tailgate nitrogen injection, although included in the base case model, is less effective as most nitrogen is exhausted directly through the tailgate return without providing a noticeable inertization effect. The fundamental behavior
between the two models is the same: the nitrogen migrates from the headgate injection points across the gob towards the tailgate return. Further, the profile of the gas distribution is similar with fresh air penetrating into the gob up to the first nitrogen injection point on the headgate side.

Figure 4.8: Comparison of EGZ contour plots: base mesh and species gradient mesh adaptation

Table 4.5: Comparison of EGZ volume prediction: base mesh and species gradient mesh adaptation

<table>
<thead>
<tr>
<th></th>
<th>Normalized EGZ Volume</th>
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</thead>
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<tr>
<td></td>
<td>Gob</td>
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<td>Base Mesh</td>
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<tr>
<td>Methane gradient mesh adaptation</td>
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</tr>
<tr>
<td>Nitrogen gradient mesh adaptation</td>
<td>0.90</td>
</tr>
<tr>
<td>Oxygen gradient mesh adaptation</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Another validation required is that of mesh independence. Mesh independence can be demonstrated by refining the mesh cells until the solution no longer changes. This is often done by refining the mesh based on a gradient. This approach captures the parameter transitions with higher accuracy by placing additional grid cells in areas where a steep gradient is predicted by the model. Each of the three gas species, oxygen, methane, and nitrogen were used to refine the mesh separately. The results from each mesh refinement were compared to the base modular mesh. The EGZ volume contour plot is given in Figure 4.8 and the total explosive volumes are given in Table 4.5. There appear to be no significant differences between the base mesh and each of the species adaptations in the EGZ contour plots. The difference in total EGZ volume between the base mesh and each of the species adaptations is within 10% of the total predicted volume for the gob. The normalized EGZ volumes in the strata agree to within 2% for all cases. This accuracy is acceptable considering the accuracy of boundary conditions and other input data.
CHAPTER 5
RESULTS: HAZARD MITIGATION IN PROGRESSIVELY SEALED PANELS

This section starts with a discussion and comparison of progressively sealed longwall panels with U-Type and back return (or inby split) ventilation schemes. Discussion includes the flow patterns inside the gob, oxygen ingress, EGZ hazards and the impact of nitrogen injection to mitigate those hazards. Discussion continues with recommendations as well as cautionary guidance for using a back return as opposed to the standard U-Type scheme. The concept and benefit of a “dynamic seal” is introduced. The nitrogen injection quantity and location is parametrically studied to determine the impact on the formation of the dynamic seal. A brief discussion regarding the economics of nitrogen injection is discussed for the rates presented in this chapter.

5.1 Flow patterns in progressively sealed U-Type ventilation and back return panels

The primary purpose of progressively sealed panels is to minimize oxygen ingress in the gob to prevent spontaneous combustion events. A standard U-Type ventilation scheme and a back return scheme are depicted in Figure 5.1. The crosscuts along the headgate are progressively sealed using seals that are constructed as the longwall face advances past each crosscut. A ventilation check curtain hung on the headgate inby the face directs the majority of the air across the face but, as shown in Figure 5.2, leakage into the gob may occur through both the curtain and through the longwall shields. In U-Type ventilation, the flow is directed across the face and returns outby through the return entries on the tailgate side. Fresh air ingress into the gob occurs within approximately the first third of the total face length. Towards the tailgate end of the face, gob gases migrate back from the gob into the face. The gob atmosphere immediately inby the face is primarily fresh air with 21% oxygen and methane content in the gob air increases towards the tailgate.

A back return is a modification of the standard U-Type ventilation scheme, see Figure 5.1. The purpose of a back return is to maintain fresh air and to remove the methane and oxygen deficient atmosphere from the tailgate corner of the face (Smith et al., 1994). To establish a back return, the outby tailgate return must be regulated and the nearest inby crosscut is left open, forcing a majority of the face air to split inby the tailgate before it flows through the open crosscut and turns to the outby direction. By regulating the tailgate in this manner, the point of lowest pressure at the tailgate side of
the face moves to the nearest crosscut inby the face. A back return works better if there is a void in the gob along the tailgate side, which is often observed. All back return results shown in this dissertation implement a 50% inby split in which 50% of the airflow is returned through the tailgate and 50% of the airflow is forced inby through the back return.

Figure 5.1: Depiction of a standard U-Type ventilation scheme (a) and a back return or inby split scheme (b)

The flow patterns inside the gob for both a U-Type and a back return ventilation scheme are shown in Figure 5.2 in the form of velocity streamlines. Lines closely spaced indicate a higher velocity gradient. The flow velocity inside the gob is low compared to the face flow. In the back return, the higher velocities extend as far back as 60 meters on the tailgate side. The face air ingress, depicted as volumetric flow through the shields, is shown in Figure 5.3. The average methane concentration in the face, calculated as the volumetric integral, is also shown for U-Type ventilation. A positive volumetric flow implies the gob air is migrating into the face. In the U-Type ventilation case, fresh air ingress into the gob occurs within approximately the first third of the total face length at which point the gob atmosphere begins to migrate back into the face through the shields. The gob atmosphere immediately inby the face is primarily composed of fresh air and the methane content increases towards the tailgate. In the back return case, face air flows consistently into the gob and gob atmosphere never enters the face. As a result, the fresh air and oxygen ingress into the gob is increased compared to U-type
ventilation. The depth of air ingress is dependent on the inby split quantity. The goal of the back return is to keep the face free of methane and to sweep the tailgate corner with fresh air. Therefore, a sufficient inby split must be maintained at all times.

Figure 5.2: General flow patterns inside a U-Type ventilation and a back return gobs. Flow direction is from headgate to tailgate in the U-Type ventilation and from headgate to the back return outlet in the back return scheme.

Figure 5.3: Volumetric flow rate of air through the shields for a U-Type ventilation and a back return as a position of shield number on the face. Methane concentration in the face is also shown for the U-Type ventilation scheme, methane concentration in the back return case is negligible.
EGZs and spontaneous combustion are the two primary ventilation related hazards in longwall coal mining regardless of ventilation scheme, technologies or strategies used to mitigate the hazard. A method to completely eliminate these hazards has yet to be developed, although nitrogen injection has been demonstrated to significantly reduce the size of EGZs (Worrall, 2012) and to partially mitigate the spontaneous combustion hazard (Balusu, 2002). Despite this knowledge, further understanding relating to optimal injection quantity and location is required to improve the effectiveness of nitrogen injection. Under base operating conditions for Mine C, 33m³/s of air flows across the face using the U-Type ventilation method. Nitrogen is injected through the first two headgate side crosscuts and the first tailgate side crosscut inby the face. The EGZ and oxygen ingress hazards for these conditions, but without nitrogen injection, are depicted in Figure 5.4. In this case, a large EGZ forms in the dilution zone between the oxygen rich and methane rich regions of the gob. For color coding, refer to Figure 4.4. Fresh air ingress is high with oxygen concentrations exceeding 17% as far as the 6th crosscut, or about 360 m, inby the face. EGZ volume is presented as a normalized value against the Mine C base case operating conditions without nitrogen injection. Therefore, the EGZ volume for the case depicted in Figure 5.3 corresponds to a normalized value of 1.

The standard nitrogen injection rates at Mine C are 0.2m³/s at the first crosscut on the tailgate side and 0.1m³/s through each of the first two headgate crosscuts, for a total of 0.2m³/s on the headgate side. The EGZ and oxygen ingress results are depicted in Figure 5.5. The fringe zone between the face and the methane-rich center of the gob is filled with nitrogen, shown in dark green on the EGZ plot, and largely inert on the plan view plot. In this case, the normalized EGZ volume has been decreased to 0.26 by implementing nitrogen injection. The amount of oxygen ingress is also significantly decreased. The oxygen concentration drops to below 3% within 120m of the face. Nitrogen injection complements the progressive sealing. As nitrogen is injected, it forms a ‘dynamic seal’ in the fringe zone, separating the fresh air ingress from the methane-rich atmosphere deep in the gob. An important point is that, with U-ventilation, the dynamic seal may not form completely across the gob, as a narrow methane rich zone forms near the tailgate corner. This area presents an EGZ hazard adjacent to the active workings area where the oxygen rich air in the longwall face mixes with methane-rich gob gases. It should be noted that the EGZ extends vertically into the gob and may be larger than what is visible in the plan view, as can be seen in Figure 5.6. This Figure shows a large EGZ near the tailgate corner immediately inby the shields which extends into the upper regions of the gob.
Figure 5.4: U-Type ventilation hazards. EGZ plot on left and oxygen ingress plot on right. No nitrogen injection, face ventilation $33\text{m}^3/\text{s}$

Figure 5.5: U-Type ventilation hazards. EGZ plot on left and oxygen ingress plot on right, with nitrogen injection. Nitrogen injection is at a rate of $0.1\text{m}^3/\text{s}$ through the first headgate crosscut, $0.1\text{m}^3/\text{s}$ through...
the second headgate crosscut and 0.2 m³/s through the tailgate crosscut. Face ventilation is 33 m³/s, this is the base case.

![Figure 5.6: U-Type ventilation vertical section directly inby the shields for the case depicted in Figure 5.4.](image)

Implementing a back return sweeps the tailgate corner with fresh air but also results in fresh air ingress deeper into the gob. The EGZ and oxygen ingress results for a back return without nitrogen injection are given in Figure 5.7. The results for nitrogen injected at a rate of 0.2 m³/s at the first crosscut on the tailgate side and 0.1 m³/s through each of the first two headgate crosscuts, for a total of 0.2 m³/s on the headgate side, are given in Figure 5.8. Using a back return without nitrogen results in an EGZ size that is noticeably larger, in this case about 26%, compared to U-Type ventilation. Further, oxygen concentrations exceed 17% for a distance of nearly 600 m inby the face.

Nitrogen injection is also effective in back return ventilation schemes. With nitrogen injection, the size of the EGZ was significantly decreased to 0.34 compared to the base case. Note that the decrease in EGZ size with nitrogen injection is equally effective for a back return (1.26 vs. 0.34 or a reduction factor of 3.7) compared to a U-Type ventilation scheme (1.0 vs. 0.26 or a reduction factor of 3.9). As shown in Figure 5.5, the dynamic seal formation from nitrogen injection without back return only extends for roughly half the panel width, at which point an EGZ forms in the upper gob atmosphere. The vertical cross-section immediately behind the shields depicted in Figure 5.9 shows that an EGZ remains in the upper regions deep within the gob. The EGZ hazard immediately inby the face has been removed. This region has been replaced with the fresh face air sweeping the tailgate corner.

Disadvantages of a back return over U-Type ventilation include increased EGZ volume, increased oxygen ingress and required maintenance of the ventilation system as the back return regulator must be adjusted continuously while the face advances. Fresh air or oxygen ingress is a concern in mines with coal exhibiting a high propensity for spontaneous combustion (Koenning, 1994). Further, the back return requires constant maintenance to operate safely and, in some cases may not be possible to implement.
Back return function is improved if a void forms in the gob along the tailgate side. With a tight caving tailgate, this method may not work as well. The main advantage of the back return scheme is the removal of methane accumulations and oxygen deficiency near the tailgate corner that frequently occur in U-Type ventilation. This concern was documented by early studies of U-Type ventilation (Thorp, 1970; Matuszewski and Lunalzewski, 1979). The implementation of a back return in a CFD model demonstrated improved tailgate air quality and, although the tailgate EGZ may not be completely eliminated, it is moved approximately 60m inby the face, away from the active workings. Since the EGZ is moved further inby the likelihood of an ignition from face equipment is unlikely. A more likely ignition source in a back return is a spon com event that has proceeded to thermal run away.

Figure 5.7: Back return ventilation hazards. EGZ plot on left and oxygen ingress plot on right, without nitrogen injection, face ventilation 33m$^3$/s and a 50% back return inby split
Figure 5.8: Back return ventilation hazards. EGZ plot on left and oxygen ingress plot on right, with nitrogen injection. Nitrogen injection is at a rate of $0.1\text{m}^3/\text{s}$ through the first headgate crosscut, $0.1\text{m}^3/\text{s}$ through the second headgate crosscut and $0.2\text{m}^3/\text{s}$ through the tailgate crosscut. Face ventilation is $33\text{m}^3/\text{s}$, this case is depicting a 50% back return inby split.

Figure 5.9: Back return ventilation: vertical section directly inby the shields. Nitrogen is injected at $0.1\text{headgate1x0.1headgate2x0.2tailgate}\text{m}^3/\text{s}$, face ventilation $33\text{m}^3/\text{s}$ and a 50% inby split.

5.2 Development of a dynamic seal in a back return scheme

Nitrogen injection, in addition to progressive sealing was shown to be effective at reducing the EGZ hazards and mitigating oxygen ingress. The purpose of this section is to investigate whether nitrogen
can be used to create a seal in the interior of the gob. This seal does not block airflow, it separates the oxygen rich ventilation air ingress from the methane rich gob atmosphere. As the nitrogen injection locations are advanced this seal will move forward, hence the term ‘dynamic seal’.

As shown in Coward’s triangle, Figure 4.4, a given gas composition cannot transition from one light green region to the other without passing through either the dark green region or the near explosive region (orange). The dark green region is nitrogen rich and lies both below the lower explosive limit for methane-air mixtures and below the oxygen threshold to support spontaneous combustion. From CFD modeling it could be shown that, if nitrogen injection results in a dark green region extending fully across the gob, it may be possible to eliminate the entire explosive fringe zone that normally forms between the face air and the methane-rich center of the gob. This phenomenon is called a “dynamic seal”. The term dynamic seal is used because, as the longwall face advances, the nitrogen injection points are also moved forward, thereby advancing the dynamic seal with the face. Therefore, spontaneous combustion and EGZ hazards are both effectively eliminated. Modeling confirmed that the gob atmosphere remains methane rich inert inby the dynamic seal.

Since methane is buoyant, EGZs may still form at elevations higher than shown by the plan view plots. Figure 5.10 indicates that small EGZs may still form in the upper gob along the interface between face air ingress and methane-rich gob gas.

![Figure 5.10: EGZ depiction on a vertical cross-section through the center of the panel. Nitrogen injection 0.8m³/s on the headgate side and no tailgate injection](image)

Further CFD modeling was performed to evaluate the nitrogen injection scheme required to form a complete dynamic seal that extends from headgate to tailgate with the implementation of a back return. Both nitrogen injection quantities and injection location were varied in this study. Using the Mine C base case, a complete dynamic seal could be formed injecting nitrogen at a rate of 0.2m³/s
through two of the headgate crosscuts (0.4m3/s total). Injection locations closer to the face were found to better reduce oxygen ingress and EGZ volume, even if the injection quantity was not sufficient to form a complete seal.

The impact on the EGZ reduction for selected modeling runs is depicted in Figure 5.11 along with the normalized EGZ volume. Studies show that the base case EGZ volume can be reduced to 7% of the base case volume with an optimized nitrogen injection scheme. A summary of injection rates and locations is depicted in graphical form by Figure 5.12. The 1st and 2nd crosscuts inby the face on the headgate side are the optimal injection locations for reducing EGZ volume. Moving the injection locations further inby increases the EGZ volume although this effect diminishes at higher injection quantities. A complete dynamic seal was formed when nitrogen was injected at rates of 0.2 and 0.2m3/s from the two headgate injection locations. Doubling the nitrogen injection quantities to a rate of 0.4 and 0.4m3/s shows that the dynamic seal becomes wider but the EGZ volume is only reduced by 5%, confirming the effect of diminishing returns first observed by Worrall (2012). Still, higher nitrogen injection rates create a wider seal that will remain effective at higher levels of oxygen ingress while a narrower dynamic seal may begin lose effectiveness with increasing oxygen ingress, d resembling what is shown in Figure 5.8.

Another important finding shown in Figure 5.11 and Figure 5.12 is the impact of changing injection locations. Injections further inby than the first two crosscuts no longer contribute to dynamic seal formation. For example, with nitrogen injected through the 1st and 7th crosscut at a rate of 0.4x0.4m3/s, the dynamic seal is similar to a case with half as much nitrogen injected from the 1st and 4th crosscuts. Nitrogen injected from the 7th inby crosscut inertizes a location that is already fuel rich inert and is therefore ineffective.

It should be noted here that the findings in regard to the nitrogen injection locations for a back return ventilation scheme differ from other researchers’ findings in U- ventilated panels. Balusu (2002) found that, for U-Type ventilation, nitrogen injection from the first and third crosscuts was more effective than injecting from the first crosscut only. Balusu’s study primarily focused on reducing oxygen content and optimum inertization strategies for panel sealing. Also, in Balusu’s studies, the source of the methane came from the floor, not the roof. The likely reason nitrogen injection schemes further inby the face are more effective in U-Type ventilation schemes is due to the gob gas flow patterns. Nitrogen injected in close proximity to the face re-joins with the face ventilation as the gob air migrates into the face whereas nitrogen injected further inby the face will remain in the gob for a longer duration.
back return scheme, the nitrogen injected into the gob is less likely to migrate back into the face due to the flow patterns in a back return gob.

![Figure 5.11: EGZ contour plot for various nitrogen injection schemes](image)

Figure 5.11: EGZ contour plot for various nitrogen injection schemes

![Figure 5.12: Impact of nitrogen injection schemes on EGZ normalized volume in a back return ventilated gob. HG refers to headgate, HG1&3 refers to injection through the first and third crosscuts and the amount shown in the legend is injection quantity through each of the two crosscuts.](image)

Figure 5.12: Impact of nitrogen injection schemes on EGZ normalized volume in a back return ventilated gob. HG refers to headgate, HG1&3 refers to injection through the first and third crosscuts and the amount shown in the legend is injection quantity through each of the two crosscuts.
5.3 Mitigation of oxygen ingress in a back return scheme

Oxygen concentration in the gob is important as it may support spontaneous combustion. The coal’s propensity to spontaneous combustion varies widely and is dependent on numerous variables discussed in the literature review. Beamish and Beamish (2012) used a moist adiabatic oven test to benchmark several different types of coal. Using this testing method, the “incubation” time for the coal until thermal runaway varied from less than 20 hours for coals with high propensity to 340 hours for coals with low propensity. Spontaneous combustion can initiate at oxygen concentrations of 10% or higher and, once initiated, can continue at oxygen concentrations as low as 6% (Highton et al., 1982). Also, at the 10% oxygen concentration threshold, methane-air mixtures are no longer explosive. The goal of the nitrogen injection scheme is to lower the oxygen below these two thresholds as quickly as possible.

For highly productive longwalls, a typical mining rate is 25m per day. To prevent spontaneous combustion of coal remnants in the gob, from either the coal bed mined or from an overlying coal bed caving into the gob, inertization to below 6% oxygen should be accomplished within the incubation time. For example, if the 6% oxygen contour reaches 60m inby the face, coal left inby the gob will be exposed for 2.4 days. If the incubation time for this coal is greater than 2.4 days, spontaneous combustion cannot develop. Nitrogen injection rates may need to be increased if the longwall face sits idle for weekends or for extended maintenance periods.

Implementation of a back return results in deeper fresh air and oxygen penetration especially near the tailgate. The nitrogen injection scheme used for this section involved injecting nitrogen from each of the first two crosscuts on the tailgate side and none from the tailgate. The oxygen ingress results are shown for nitrogen injection location for the following quantities: 0.1m$^3$/s through each of the listed headgate crosscuts (Figure 5.13) and 0.2m$^3$/s through each of the listed headgate crosscuts(Figure 5.14). The higher injection quantity formed a complete dynamic seal. In the lower injection quantity scheme the oxygen content reaches the 6% threshold within 180m or 7.2 days. In the higher injection quantity scheme the 6% threshold is reached within 120m or 5 days. In Figure 5.13, for all injection locations, at roughly 100m inby, the oxygen concentration drops rapidly from fresh air to below the 6% threshold. The distance of 100 m, equivalent to four days of production, corresponds to the approximate location of the first nitrogen injection crosscut.
Figure 5.13: Oxygen ingress distance for nitrogen injection at a rate of 0.1 m$^3$/s at each given crosscut location; 0.2 m$^3$/s total headgate nitrogen injection, no tailgate nitrogen injection. HG 1 refers to the 1$^{st}$ crosscut in by the face on the HG side, HG 7 refers to the 7$^{th}$ crosscut in by the face.

Figure 5.14: Oxygen ingress distance for nitrogen injection at a rate of 0.2 m$^3$/s at each given crosscut location; 0.4 m$^3$/s total headgate nitrogen injection, no tailgate nitrogen injection.
The results shown assume that nitrogen injection is implemented immediately after mining of the panel begins. This is the recommended best practice to reduce the risk of EGZ and spontaneous combustion hazards. A transient or time dependent model was completed to study the flow of nitrogen into the gob and the formation of the complete dynamic seal. The quantity of nitrogen injection was increased to accelerate the formation of the dynamic seal for visualization purposes. Increasing the injection rate does not change the dynamic seal location but it makes it thicker. The nitrogen injection rate was set at 0.4m3/s from each of the first two headgate nitrogen injection locations and no nitrogen injection from the tailgate. The transient formation of EGZs for U-Type ventilation (a) and a back return (b) is depicted in Figure 5.15. The transient study reveals why the back return can form a complete dynamic seal while the U-Type ventilation method does not. In the U-Type ventilation scheme, most of the nitrogen travels along the flow path lines in the gob from the injection point to the tailgate return. Near the tailgate corner, nitrogen begins to migrate into the face so that, a complete dynamic seal is difficult to form. In a back return scheme, the nitrogen also follows the streamlines but the flow direction stays away from the tailgate. The nitrogen travels towards the back return and, when injected at a sufficient rate, allows for the formation of a complete dynamic seal from headgate to tailgate.

Figure 5.15: Formation of the dynamic seal using nitrogen injection in U-Type ventilation (a) and back return (b) schemes. Starting initial conditions are for 0m3/s of nitrogen injection, face ventilation quantity of 33m3/s and a 50% inby split in the back return case
5.4 Panel inertization after mining and panel sealing

One area that has yet to be researched is the formation and duration of EGZs during and after panel sealing. After a longwall panel has been mined out and sealed, methane continues to liberate from the surrounding strata. Methane emission and oxidation of the coal will eventually render the entire sealed gob inert. It should be recognized that, following completion of the seals, the sealed gob atmosphere may pass through the explosive range forming one or more EGZs. The Sago mine explosion disaster in 2006 occurred in a mine known to have only small amounts of methane. An explosion occurred in a mined-out and sealed area 22 days after sealing. The estimated average methane concentration at the time of the explosion was 13.1% (Gates et. al. 2007). Further, elevated oxygen levels in the sealed gob could initiate spontaneous combustion. A panel is considered inert once the oxygen concentration is low enough to no longer support spontaneous combustion and after all EGZs have ceased to exist.

Data collected from Australian mines (Balusu et al., 2002) revealed that the duration of oxygen concentrations above 5% can range from a few hours to several weeks depending on methane emission rates and gob characteristics. Nitrogen injection into the sealed gob can accelerate inertization.

Fauconnier and Meyer (1986) developed a mathematical model that incorporated seal leakage to analyze the effects of nitrogen injection into a sealed area. This model was developed to assist mine management in fire and explosion prevention decisions. The Fauconnier and Meyer model did not consider barometric pressure changes and treated the gob gas mixture as homogeneous. Balusu et al., (2002) used CFD modeling to investigate optimal nitrogen injection strategies to reduce the oxygen concentration below 12% in a U-Type ventilation scheme. Balusu’s recommendations were successfully demonstrated in a field study in an Australian coal mine. An empirical approach developed by Zipf (2010) used the principle of conservation of mass to create a composition change model simulating inertization and seal leakage either into or out of the sealed space. Zipf’s model considers barometric pressure fluctuations but the gas composition within the gob is treated as homogeneous. Zipf found that low amounts of methane liberation contributed to prolonged panel inertization times ranging from several days to several weeks while high methane emission rates led to a faster inertization. Yuan and Smith (2014) used CFD to model nitrogen injection into a sealed gob to mitigate spontaneous combustion. They found that a higher nitrogen injection rate did not necessarily result in a more effective inertization outcome because it also caused more leakage through the seals.
A CFD model was created to investigate the formation and duration of EGZs in longwall gobs and to determine the impact of methane emission rate on the formation, extent, location and duration of EGZ hazards after a panel has been sealed. Oxygen concentrations were evaluated as the indicator parameter for inertization. The study was completed for a U-Type ventilation scheme. Initial starting conditions for transient studies were the base operating conditions for Mine C. Once the panel had been sealed, it was allowed to self-inertize through methane emission while oxidation reactions were not modeled. Induced inertization using nitrogen injection was also investigated. Nitrogen was injected from the headgate and tailgate. The nitrogen injection locations are shown in Figure 5.16.

Figure 5.16: Transient run setup initial starting solution is from the case shown on left, boundary conditions for the transient run given on right. Nitrogen injection was only used in two cases – for the remaining cases no nitrogen was injected.

The base methane liberation rate in the model is 0.5m3/s; this will be referred to as Case 1. Two additional runs were completed with double (Case 2: 1.0m3/s) and triple (Case 3: 1.5m3/s) the methane emission rate. These values correspond to findings from Kissell (2006) that placed bounds on the gassiness of coal seams. The values were given in terms of volume of methane per metric ton of coal. Using Kissell’s gas content values a methane flowrate was calculated using the same assumptions made to create the economic model discussed in Section 5.5. The base methane emission rate, Case 1, correspond to a borderline gassy/non-gassy, Case 2 and Case 3 fall into the moderately gassy classification. For comparison purposes a similar classification system by the China Administration of Coal Mine Safety (CACMS) is compared to Kissell’s values in Table 5.1. In these three cases, nitrogen injection was not implemented. For the inertization studies presented in this section the panel was considered inert when either oxygen concentration dropped below 10% or methane concentration
exceeded the upper explosive limit of 15%. Analysis of spontaneous combustion used the 6% oxygen threshold, below which the oxidation reactions can no longer propagate (Highton, 1982).

Table 5.1: Methane Liberation from Gob Mine Classifications

<table>
<thead>
<tr>
<th>Category (Chinese)</th>
<th>US Standards (Kissell, 2005)</th>
<th>Chinese Standards (CACMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly gassy mine</td>
<td>3.09 m³/s</td>
<td>1.4 m³/s</td>
</tr>
<tr>
<td>Moderately gassy mine</td>
<td>1.33 - 3.09 m³/s</td>
<td>1.1 - 1.4 m³/s</td>
</tr>
<tr>
<td>Gassy mine</td>
<td>0.44 - 1.33 m³/s</td>
<td>0.7 - 1.1 m³/s</td>
</tr>
<tr>
<td>Non-gassy mine</td>
<td>0 - 0.44 m³/s</td>
<td>0.4 - 0.7 m³/s</td>
</tr>
</tbody>
</table>

Two additional modeling cases evaluated the effectiveness of nitrogen injection to reduce the duration of EGZs and elevated oxygen concentration in the gob. Case 4 implemented nitrogen injection only after the panel had been sealed. In Case 5, continuous nitrogen injection was implemented during active mining and was continued throughout the sealing process. The methane emission was left at the base methane emission rate from Case 1 (0.5m³/s). Nitrogen was injected at a rate of 0.19m³/s through seals on the headgate and tailgate gate sides as shown in Figure 5.15. The summary of cases is presented in Table 5.2.

Table 5.2: Modeled Cases and Description

<table>
<thead>
<tr>
<th>Case</th>
<th>Modeled Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.5m³/s of methane liberation, no nitrogen</td>
</tr>
<tr>
<td>Case 2</td>
<td>1.0m³/s of methane liberation, no nitrogen</td>
</tr>
<tr>
<td>Case 3</td>
<td>1.5m³/s of methane liberation, no nitrogen</td>
</tr>
<tr>
<td>Case 4</td>
<td>0.5m³/s of methane liberation, 0.4m³/s nitrogen injection after sealing</td>
</tr>
<tr>
<td>Case 5</td>
<td>0.5m³/s of methane liberation, 0.4m³/s nitrogen injection before and after sealing</td>
</tr>
</tbody>
</table>

5.4.1 Impact of methane emission rate

The first three cases listed in Table 5.2 were used to determine the impact of methane emission rate on gob hazards during sealing. The CFD model prediction of maximum oxygen concentration in the gob is given in Figure 5.17. Average concentrations are much lower but, for assessing spontaneous combustion risk, the maximum oxygen concentration is more relevant. The maximum initial oxygen concentration is at atmospheric levels. The bold black line in Figure 5.17 depicts the 6.0% oxygen
threshold. In the base case, the duration of oxygen concentrations above 6% is approximately 18 days. In Case 2 and 3, the 6% oxygen threshold is reached around 10 days and 7 days respectively. This confirms the findings by Balusu et al., (2002) and Zipf (2010) that less gassy mines are at risk for spontaneous combustion for a longer duration. When the coal is prone to spontaneous combustion, less gassy mines should consider supplemental inert gas injection to speed the gob inertization process.

Figure 5.17: Maximum oxygen concentration in the gob with respect to time after the panel has been sealed

It should also be recognized that the sealed atmosphere will pass through the explosive range, forming EGZs. Oxygen trapped behind the seals is mixed with methane gas emitted from the surrounding strata. Figure 5.18 depicts the transient transformation of the EGZ in day-by-day snapshots for Case 1. On Day 1 the EGZ has not changed noticeably. On day 2, there is a small EGZ forming directly behind the recovery room. On Day 3, the merged EGZs continue to grow. The two initial EGZs from day 2 have merged has and have pushed into the recovery room. On Day 4, most of the recovery room is explosive. On Day 5, the EGZ volume begins to shrink as methane displaces oxygen. The EGZs near the headgate and tailgate are particularly concerning as these areas could be prone to either seal leakage resulting in fresh air leaking into the gob. The EGZs in these regions are still present 6 days after sealing the panel. At higher methane emission rates the EGZ forms in similar fashion but the duration is shorter.
Figure 5.18: Transient formation and location of EGZs in the gob depicted in daily increments for Case 1. Note that the recovery room fills with an EGZ during Days 3 to 5.

The duration and relative size of the EGZ with respect to time is given in Figure 5.19 for the gob and Figure 5.20 for the longwall recovery room. EGZs will form when the panel is allowed to self-inertize, and there is potential for EGZs to form directly behind the seals. In Case 1, the EGZ increased in size before reaching a maximum volume after Day 4. At this point, the methane concentration in the gob began to exceed the upper explosive limit and EGZ locations within the panel began to self-inert. Still, the panel contained EGZs for 9 days. For Cases 2 and 3, the maximum EGZ volume was reached after roughly 17 hours and 10 hours, respectively. The EGZ in the recovery room was present for over 6 days in Case 1, 4 days in Case 2 and 2 days in Case 3.
5.4.2 Using nitrogen injection to mitigate EGZ hazards during sealing

Nitrogen or inert gas injection has been routinely used by Australian coal mines for the last decade (Balusu, 2002). In the U.S., nitrogen inertization is only used by a few mines. Two cases were created to research the effectiveness of nitrogen injection after the panel had been sealed. Case 4 implemented nitrogen injection only after the panel had been sealed, no nitrogen injection was used during active
mining. In Case 5, continuous nitrogen injection was implemented during active mining and was continued throughout the sealing process. The methane emission was left at the base methane emission rate from Case 1 (0.5m$^3$/s). Nitrogen was injected at a rate of 0.19m$^3$/s through seals on the headgate and tailgate gate sides. This study demonstrates the benefit of nitrogen injection for mitigating the EGZ and spontaneous combustion hazards after a panel has been sealed. Figure 5.21 shows the maximum oxygen concentration in the gob over time, following final sealing. The benefit of nitrogen injection is more pronounced in Case 5 where nitrogen injection was used during mining and continued throughout the sealing process. In Case 4, the time to reach the 6% spontaneous combustion threshold is similar to the base case without nitrogen injection. In Case 5, the maximum oxygen concentration drops below the 6% threshold in roughly 6 days.

![](image)

Figure 5.21: Maximum oxygen concentration in the gob with respect to time after the panel has been sealed and nitrogen injection is used to accelerate inertization

The benefit of nitrogen injection during panel sealing is significant as seen in Figure 5.22. EGZs were eliminated within 6.5 days for Case 4 and within 3 days for Case 5. The formation of EGZs is depicted in Figure 5.23. With nitrogen injection, no EGZ formed in the recovery room. The nitrogen dilutes the oxygen before the methane concentration exceeds the lower explosive limit.
Another benefit of nitrogen injection is that the area directly behind the seals is maintained fuel lean inert rather than fuel rich inert and fresh air leaking through the seals during barometric pressure rises cannot form an EGZ. A strategy by Balusu et al., (2002) injecting nitrogen at higher quantities rendered the gob atmosphere inert within hours. Yuan and Smith (2014) found that, when seal leakage was incorporated in the model, nitrogen injection would increase seal leakage and had a diminishing effect on inertization.

Figure 5.22: Normalized EGZ volume in the gob with respect to time after the panel has been sealed and nitrogen injection is used to quicken inertization

Figure 5.23: Transient formation and location of EGZs in the gob; depicted in 24 hour increments
5.5 Model sensitivities

Numerical modeling is a useful research tool that allows parametric studies of numerous variables within a relatively short time frame compared to experimental studies. One drawback of numerical modeling is the uncertainty of results. Numerical models should, when possible, be validated with experimental studies. Numerical models of the airflow and gas distributions inside the gob cannot be easily validated with experimental studies due to lack of physical access that limits obtaining data beyond the fringes of the gob. As a result, the errors of the CFD model must be bound through sensitivity studies aimed at determining the significance of each variable of model results.

Worrall completed several sensitivity studies in order to bound the results of his model. He investigated the permeability of both the gob and the fractured zone, the effect of a void along the fringes of the gob, the methane emission rate, GVB suction pressures or flow rates and the impact of only modeling a portion of the gob rather than the entire panel to justify saving computational time. He concluded his model predicted that the volume of EGZs decreased with increasing headgate nitrogen injection rates and that increasing the face ventilation quantity resulted in a lower tailgate methane concentration but an EGZ volume. He also concluded that neither finding appeared to be sensitive to the various uncertainties resulting from modeling the longwall gob in a CFD domain. He also concluded that using a distributed permeability, rather than a uniform permeability distribution within the gob, made a significant difference on final results. The permeability distribution ensures the center of the gob is assigned a lower permeability value which increases towards the edges of the gob and around both the startup rooms and location of the active face. He concluded that neglecting this distribution skewed the resulting gas distributions and allowed additional oxygen ingress. The presence of a void along the edges of the gob was also important. Mines without such void, where the gob caves tightly against the pillars, do not permit the amount of oxygen ingress compared to models with a void. Worrall also concluded that the model is not sensitive to the permeability magnitude assigned to the fractured zone, an area where the assigned values are uncertain and assigned as a constant value.

The following discussion summarizes an attempt to characterize the sensitivity of the CFD model to a variety of user-inputs and geometry configurations. The geometry configuration studies involved using an actual longwall shield face model as opposed to a simplified leakage port used by Worrall (2012). Additional sensitivity studies include applying multipliers to the gob permeability distribution used in this dissertation, evaluation of different methane emission rates, a nitrogen injection purity study and
varying the amount of airflow sent through the back return. The multipliers applied to the permeability distribution are x10, x2, x0.5 and x0.1; for reference, the permeability in Mine E is approximately ten times the permeability in Mine C. Methane emission rates were selected from research by Kissell (2006) for US coal mines; the base methane emission rate in this model is 0.5 m³/s which falls into the ‘moderately gassy’ classification, two additional runs were completed for a ‘mildly gassy’ and a ‘highly gassy’ methane emission quantity. The purity of the nitrogen injection is an important parameter for implementation of nitrogen generators in the industry. As reported by Mine E, which uses a membrane plant to create nitrogen, the purity of the nitrogen varies from 99% to below 95% depending on the injection quantity.

5.5.1 Face model variations

Accurate depiction of the longwall face and the shields themselves has proven difficult to implement in CFD models. Previous attempts have included modeling communication from the longwall face to the gob as a porous media jump (Yuan and Smith, 2014). The porous media jump assigns a user specified pressure drop across this interface, any flow into the gob is automatically slowed by the porous media jump. Worrall (2012) included modeling the gaps between the shields themselves as shown in the left image of Figure 5.24. Other researchers on CFD modeling of longwall gobs are Balusu (Balusu et al. 2005) and Ren (Ren and Wang, 2013). Balusu’s work does not state how the interface between the face and the gob is modeled. Ren and Wang created a model of the face using actual longwall shields and validated the model against field ventilation survey data. The purpose of this model was to study gas and dust dispersion patterns in the face and therefore the gob was not included. The geometry of the longwall shields used for the findings from this dissertation are depicted in the right image of Figure 5.24.

Figure 5.24: Comparison of leakage port longwall face model by Worrall (2012) on the left to the model discussed in this research, a longwall face model using actual longwall shields on the right.
Results from the two longwall face models are compared in Figure 5.25. Modeling the longwall face using the geometry of the longwall shields increases the resistance and therefore, the pressure drop across the face. The amount of oxygen ingress is increased and the profile changes from wedge shaped in the leakage port model to a profile that resembles a square. In three dimensions, the oxygen ingress resembles a ‘dome’ and is not symmetric from headgate to tailgate. Other differences include a drop in the percentage of methane exhausted by the GVB’s. The leakage port model exhausts approximately 99% and 98% methane through the two GVBs, the remainder is oxygen and nitrogen at roughly the same distribution found in air, 78% nitrogen and 21% oxygen. In the longwall shield model the methane percentage drops to 83% and 92% methane, the remainder is mostly nitrogen at a higher percentage than that of air suggesting that some of the headgate nitrogen is exhausted through the GVBs rather than face air. This hypothesis was confirmed through ‘tracer gas studies’ in the CFD model completed by assigning a different gas species at each injection location while keeping the properties the same as nitrogen gas.

Figure 5.25: Comparison of leakage port longwall face model (left) to the model discussed in this research: a longwall face model using actual longwall shields (right). Image depicts a back return scheme.

Several important similarities also exist between the two models. The impact of tailgate nitrogen injection is not as effective as injection from the headgate side, evident from the lack of penetration into the gob in both models. Nitrogen injected from the tailgate side is quickly exhausted through the tailgate return before it can penetrate into the gob and dilute potentially explosive mixtures.
similarity is the existence of an EGZ directly inby the face on the tailgate side and the presence of a methane rich zone directly adjacent to this region. The final similarity between the two models is that the gob atmosphere becomes methane rich inert within several hundred meters and well within the 450m rear bound of the models shown below. This is further evidence that modeling the entire longwall panel is not necessary to study gas distributions within the first 100 meters inby the face.

5.5.2 Permeability bounding

As described in Chapter 3, an accurate geo-mechanical model of a longwall mine was developed that could be verified against field measurements. The findings presented in this dissertation were determined using the geomechanical model of Mine C, where the roof rock is made up of mudstone and shale and caves into small particle sizes. The caving mechanisms varies widely from mine to mine as evident from comparison of the results from Mine C and Mine E. Mine E was not covered in detail, however the permeability in Mine E is approximately an order of magnitude greater than that of Mine C. Due to the large difference between the two mines, a sensitivity study was completed on permeability. The study consisted of changing the permeability from one-tenth, one-half, twice and 9.3 times (Mine E) of the base Mine C permeability.

The results of the sensitivity study are presented in Figure 5.26. As expected, the permeability of the gob has a significant impact on the amount of oxygen ingress. The formation of the dynamic seal occurs for all permeability values except the x0.1 Perm case, which is one tenth of the base Mine C permeability. In the x0.1 Perm case, the dynamic seal is formed but approximately 50% of the nitrogen injected returns to the face, although it is eventually exhausted through the back return. This scenario is concerning given the fact that excess nitrogen can dilute oxygen content in the face where miners are working. This impact was small when evaluating the oxygen content in the tailgate return yet localized spots may exist that are close to or do not meet regulatory requirements of 19.5% oxygen.

The total volume of explosive gas increases with increased permeability but, at the same time, the EGZ zone is move further back and higher into the gob. To prevent spontaneous combustion mitigation, oxygen ingress must be minimized. Mine operators cannot control how the gob caves so other solutions need to be examined for gobs that cave much tighter and much looser than the findings presented for Mine C.
5.5.3 Methane Emission bounding

The methane emission rate was one of the more difficult parameters to ensure fidelity to actual conditions in the mining environment. The methane was modeled as a constant and independent of location. The methane emission rate likely decreases to a constant value further away from the active face. The face itself should have a higher emission rate than further inby. The main source of emission on the face is the shearer cutting fresh coal, further inby the source of emissions is from the caving of overlying strata layers that contain methane. Kissell (2006) studied the emission rates of US longwall mines in terms of volumetric methane per ton of coal.

The purpose of this section is to understand the sensitivity of the model's response to a range of methane emission rates. Kissell’s created three categories of methane emission rates which included highly gassy, moderately gassy and mildly gassy with methane emission rates given in Table 5.1. Three models were run with high, moderate and mild emission rates. The EGZ contour plots are depicted below in Figure 5.27. The emission rate has a noticeable impact on the amount of oxygen ingress. The flow far inby the gob becomes diffusion driven rather than momentum driven, by increasing the amount of methane in the model the oxygen ingress decreases since it is quickly diluted by methane. The dynamic seal is complete in both the low and high emission rate cases. The fact the dynamic seal formation is not complete in the base emission rate case was a surprising finding. Upon review of the
solution settings there was a discrepancy between convergence criteria on species. The difference between the base case and the high and low was small, 5x10^-4 compared to 1x10^-4. The model was not re-run because the initial case file used to create all three models was unavailable at the time of writing. The difference in total volume of explosive gas is difficult to determine from contour plots. Analyzing the data generated from each model showed an increase in EGZ volume by 20% for the low methane emission rate and a decrease by 46% for the high methane emission rate.

Figure 5.27: Impact of methane emission rates on gob gas distributions and the formation of a dynamic seal in a back return scheme.

5.5.4 Nitrogen injection purity

The mine presented in the CFD portion of this research utilizes nitrogen supplied by a third party vendor. The vendor produces the nitrogen for a variety of customers via a cryogenic process and very high purity can be obtained, upwards of 99.9%. Economy of scale makes the cryogenic process a favorable consideration only when a significant amount of production is desired and the investment can be justified. Less expensive processes include membrane plants that can be purchased as modular units. The downside to using membrane plants is that the purity of the nitrogen produced is a function of required production. One of the mines visited shared that they can produced nitrogen at 99.5% pure nitrogen at 0.4 m3/s, 98% pure nitrogen at 0.6 m3/s or 95% pure nitrogen at 0.75 m3/s.

The purpose of this section is to understand the sensitivity of the model’s response to the purity of nitrogen injected. In the study three models were ran with 100% pure nitrogen, 98% nitrogen and 95%
nitrogen. The rate itself was left constant to ensure any impacts were isolated to nitrogen purity. The EGZ contour plots are depicted below in Figure 5.28. The injection quantity was left constant therefore no impact on oxygen ingress was expected. The completeness of the dynamic seal is impacted. In the first two cases, 100% and 98% the difference is negligible. In the 95% case, the dynamic seal is not complete and terminates approximately halfway across the panel, at this point an EGZ forms. Additional oxygen in the nitrogen injection decreases the effectiveness and can increase the risk of a spontaneous combustion event if the oxygen exceeds 6%.

![Figure 5.28: Impact of permeability on gob gas distributions and the formation of a dynamic seal in a back return scheme.](image)

5.6 Economic analysis of nitrogen injection rates

An economic model used for this analysis was constructed by Grubb (2008) to examine the feasibility of preventive measures for spontaneous combustion collectively and individually. The model was updated to incorporate nitrogen injection costs supplied by Mine C. The method of accounting for the cost of nitrogen injection also needed to be updated from Grubb’s methodology.
The original economic model was developed to compare the economic impact of a spontaneous combustion event to the cost of continuous nitrogen injection for a cost-benefit analysis. The model used for the analysis was the “Selected Practices” case described by Grubb (2008). This case is very similar to the actual practices used by Mine C. It involves a progressively sealed panel utilizing a tube bundle system for gas analysis, nitrogen injection into active panels in addition to pressure balance chambers installed in completed panels to mitigate spontaneous combustion and EGZ hazards and gob ventilation boreholes to control methane near the tailgate.

5.6.1 Key assumptions

A list of key parameter assumptions incorporated into Grubb’s model are given in Table 5.3. A sale price of $25.00 per ton of coal was assumed. Mining equipment included a super-section with two continuous miner units to develop the mains, a standard continuous miner section for panel development and 330 meter wide longwall panels. Support systems, coal handling and preparation facilities were assumed typical for a comparably sized underground longwall mine. Infrastructure costs were only applied to the mine property assuming that the location was adjacent to existing infrastructure. An assumption that the mine is one of several assets owned by a publically traded mining corporation was made for tax calculations and estimation of overhead.

Grubb (2008) also used the following assumptions in the construction of the cash flow model.

- An annual inflation rate of 3% was applied to revenue, capital costs and operating costs
- Royalties and state and federal taxes are given in Table 5.4
- Depreciation for mine equipment was applied using Modified Accelerated Cost Recovery System (MACRS) rates for mine equipment developed by Stermole and Stermole (2006)
- Depreciation for buildings treated the buildings as real property
- Development costs were applied in year zero
- Property taxes, contracted services and office operating costs were included in the local administrative and technical costs
- Overhead costs included corporate administered and provided services including insurance, bonding, permitting, legal services, general human resource services, public relations, general financial services and general management. Overhead costs were set at $1.65/metric ton
- Salvage value of equipment at closure was set at one-third the undepreciated value and applied the following year
- Closure costs were estimated, escalated and applied the year following closure
Table 5.3: List of key mine parameter assumptions for cash flow model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of coal in place (metric ton per cubic meter)</td>
<td>1.3</td>
</tr>
<tr>
<td>Average depth of cover (meters)</td>
<td>213</td>
</tr>
<tr>
<td>Seam thickness taken during development (meters)</td>
<td>3</td>
</tr>
<tr>
<td>Seam thickness taken by longwall (meters)</td>
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</tr>
<tr>
<td>Width of development entries (meters)</td>
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<tr>
<td>Number of mains entries</td>
<td>7</td>
</tr>
<tr>
<td>Mains development centers (x-cut x adv. in meters)</td>
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</tr>
<tr>
<td>Number of panel entries</td>
<td>3</td>
</tr>
<tr>
<td>Panel development centers (x-cut x adv. in meters)</td>
<td>30</td>
</tr>
<tr>
<td>Average longwall panel width (meters)</td>
<td>305</td>
</tr>
<tr>
<td>Average longwall panel length (meters)</td>
<td>3,050</td>
</tr>
<tr>
<td>Daily mains development mining rate (meters / day)</td>
<td>26</td>
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<tr>
<td>Daily panel development mining rate (meters / day)</td>
<td>52</td>
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<tr>
<td>Longwall retreat rate (meters / day)</td>
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<tr>
<td>Work days / year</td>
<td>360</td>
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<tr>
<td>Development production days / year</td>
<td>345</td>
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<tr>
<td>Longwall production days / year</td>
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<td>16</td>
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<tr>
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</tr>
<tr>
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<td>Total panel advancement in meters</td>
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<tr>
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<tr>
<td>Total longwall panel retreat in meters</td>
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</tr>
<tr>
<td>Reserves (millions of metric tons)</td>
<td>101,000</td>
</tr>
</tbody>
</table>

Table 5.4: Tax and royalty assumptions applied to economic model

<table>
<thead>
<tr>
<th>Tax and royalty assumptions</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>State income tax rate</td>
<td>5.00%</td>
</tr>
<tr>
<td>Federal income tax rate</td>
<td>35.00%</td>
</tr>
<tr>
<td>State severance tax / metric ton of coal</td>
<td>$0.61</td>
</tr>
<tr>
<td>Federal reclamation tax / metric ton of coal</td>
<td>$0.17</td>
</tr>
<tr>
<td>Federal black lung tax / metric ton of coal</td>
<td>$1.21</td>
</tr>
<tr>
<td>County sales tax / metric ton of coal</td>
<td>$0.83</td>
</tr>
<tr>
<td>Royalty rate paid to mineral rights owner</td>
<td>5.00%</td>
</tr>
</tbody>
</table>
5.6.2 Nitrogen injection costs

Mine C utilizes nitrogen supplied from a vendor operating a nearby cryogenic nitrogen plant. All capital costs regarding the nitrogen inertization system were set at zero since the plant is 3rd party owned and operated. Operating costs for nitrogen generation were provided by Mine C. Nitrogen injection is assumed to be continuous to prevent spontaneous combustion events when the longwall is down for maintenance or when the panel is finished and the shields are pulled.

Evaluated nitrogen injection rates included quantities of 0.2m$^3$/s, or the base injection rate for Mine C, 0.4m$^3$/s, 0.6m$^3$/s, and 0.8m$^3$/s. The annual operating costs assuming continuous nitrogen injection, 365 days per year and 24 hours per day, are given in Table 5.5 along with impact to the cash flow of the mine. The annual cost is determined using a piecewise function in Equation 5.1, due to a nitrogen cost increase at 0.5m$^3$/s. From the CFD studies, a nitrogen injection rate of 0.4m$^3$/s from the headgate side resulted in minimal oxygen ingress and was an appropriate injection quantity to reduce EGZ volume by forming a complete dynamic seal.

Table 5.5: Operating cost of nitrogen injection for case comparison, 0.1m$^3$/s is base case. Rate are based on information provided by Mine C

<table>
<thead>
<tr>
<th>Usage (m$^3$/s)</th>
<th>Cost per 0.2m$^3$/s</th>
<th>Annual Cost</th>
<th>NPV @ 15% (in $000's)</th>
<th>DCF-ROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>$0.68</td>
<td>$0</td>
<td>$42,033</td>
<td>0</td>
</tr>
<tr>
<td>0.4</td>
<td>$0.68</td>
<td>$840,960</td>
<td>$38,602</td>
<td>($3,431)</td>
</tr>
<tr>
<td>0.6</td>
<td>$1.52</td>
<td>$2,207,520</td>
<td>$32,748</td>
<td>($9,285)</td>
</tr>
<tr>
<td>0.8</td>
<td>$1.52</td>
<td>$2,943,360</td>
<td>$29,821</td>
<td>($12,212)</td>
</tr>
</tbody>
</table>

\[
NPV_{\text{Reduction}}(\text{in $000's}) = \begin{cases} 
-7,819 Q_{N2} - 465 & \text{if } 0.00 \leq Q_{N2} \leq 0.48 \text{ m}^3/\text{s} \\
-15,405 Q_{N2} - 504 & \text{if } 0.48 \leq Q_{N2} \leq 1.90 \text{ m}^3/\text{s} 
\end{cases} 
\] (5.1)

5.6.3 Cost-benefit analysis of nitrogen injection quantity

Only cases involving lost production were analyzed. When a spontaneous combustion event is discovered, the longwall and other mining areas must be sealed until the combustion can be extinguished. During this time, mine production is stopped and resumed after extinguishment. It was
assumed that no loss of coal reserves or equipment resulted from the event and that only one event occurred over the life of the mine. Due to the preventive measures already in place at the mine to raise awareness regarding spontaneous combustion events (from Grubb, 2008) it was assumed that a spontaneous combustion event would not occur before year 4, the second year of longwall production. Economic impacts from the event include lost or delayed revenue and costs associated with fire-fighting, Grubb (2008). The mine life was extended to allow for mining of all reserves and the lost production cases were applied for one, three, six, nine, and twelve month durations.

The resulting net present value for a spontaneous combustion event occurring in a given year is shown in Figure 5.29. The net present value for continuous nitrogen injection at a rate of 0.2, 0.4, 0.6 and 0.8 m$^3$/s are included for cost benefit analysis purposes. The net present values were calculated using a fifteen percent discount rate.

Comparison of the resulting impact on net present value cash flow for a given spontaneous combustion event occurring and various nitrogen injection rates allows for a cost benefit analysis of nitrogen injection quantity. Figure 5.29 reveals the following:

- Nitrogen injection is financially beneficial in the event it prevents a spontaneous combustion event.
- The optimal nitrogen injection rate from the CFD models suggested a rate of 0.4 m$^3$/s. Continuous injection at this rate results in a lower impact to NPV for all spontaneous combustion events except for a one month mine closure, a 3 month mine closure occurring after 11 years or a 6 month mine closure occurring after 15 years.
- If the mine suffers a spontaneous combustion event that results in a mine closure for longer than 6 months there is more financial loss than continuous nitrogen injection at a rate of 0.4 m$^3$/s.

The likelihood of a spontaneous combustion event occurring, particularly long duration events is low given the preventative measures already implemented in progressively sealed panels. The CFD studies concluded the optimal injection quantity that formed a complete dynamic seal was 0.4 m$^3$/s. Increasing the injection rate decreased the EGZ volume. A point of diminishing returns was reached as the financial costs of nitrogen injection increased. Due to site specific conditions mines that wish to use nitrogen injection should perform their own studies to determine the appropriate injection quantity and scheme.
5.7 Summary of findings and recommendations

A back return ventilation scheme was evaluated as a means to control the EGZ hazard immediately behind the tailgate shields, a common issue with U-Type ventilation. The back return moves the EGZ in by the face and away from the tailgate regardless of nitrogen injection. Another benefit of adding a back return is that the face maintains a higher pressure than the gob over the entire length, effectively preventing the gob atmosphere from migrating back into the face. Finally, implementation of a back return in combination with nitrogen inertization enables the formation of a dynamic seal that largely eliminates EGZs. The primary disadvantage of using a back return is the increased oxygen ingress near the tailgate that can promote spontaneous combustion and potentially be an ignition source of any EGZ.
inby the gob. Another disadvantage is that maintaining the airway is difficult, particularly in poor ground conditions.

For a back return scheme, nitrogen injection was shown to be effective at reducing both the size of EGZ hazards and oxygen ingress that might promote spontaneous combustion. An EGZ may form in the upper regions of the gob and was not eliminated even at higher nitrogen injection rates, up to 0.8m3/s. The concept of a dynamic seal, separating the oxygen-rich face ventilation air from the methane-rich gob atmosphere, was proven effective with nitrogen injection. The dynamic seal forms in the dilution zone between the fresh air inby the face and the gob atmosphere and prevents EGZs from forming in the lower regions of the gob. A back return promotes the formation of a complete dynamic seal that extends from the headgate injection point across the gob to the inby split return. A complete dynamic seal was formed when nitrogen was injected at a rate of 0.4m3/s from the headgate side. Nitrogen injection from the tailgate is rather ineffective in both U-Type ventilation and back return schemes. The nitrogen injection location was shown to be most effective immediately inby the face. EGZ volume increased when the injection location was moved further inby.

A common misconception in the mining industry is that mines with low methane emission rates are safer than mines with higher methane emission rates. As seen in the Sago mine explosion, mines will form EGZs in sealed areas regardless of the methane emission rate. Modeling showed that EGZs in mines with low methane emission rates remain in the explosive range for a longer duration compared to mines with higher emission rates. Nitrogen injection after panel sealing significantly reduced both the size and the duration of both EGZ and spontaneous combustion hazards. When nitrogen is used to accelerate the inertization process, EGZs in the recovery room may be prevented. Continuous nitrogen injection throughout the sealing process is recommended as it effectively mitigates the EGZ risk during active mining and accelerates inertization time once the panel has been sealed.

A typical longwall coal mine cash flow model created by Grubb (2008) was used to investigate the economic benefits of nitrogen injection. Nitrogen injection costs were updated using information provided by Mine C and the methodology of determining nitrogen usage was updated to reflect findings from the CFD studies. The net present value of nitrogen injection was compared to the economic impact of a spontaneous combustion event. The results show that a spontaneous combustion event can have a significant impact on the mine’s net present cash flow. Longer duration events and events that occur early in the mine life have a greater economic impact. The cost of nitrogen injection is far smaller than that of a spontaneous combustion event.
CHAPTER 6

CONCLUSIONS

The primary objective of this dissertation was to study nitrogen injection strategies for mitigation of spontaneous combustion and EGZ hazards in progressively sealed longwall panels implementing a back return. The CFD models of longwall gob gas composition produced from this research can be used as a tool to predict methane explosion and spontaneous combustion hazards in longwall gobs. Modeling also promotes understanding of the effectiveness of various explosion and fire hazard mitigation strategies. The inaccessibility of the gob makes direct measurement of gas compositions inside the gob difficult. Therefore, gas compositions and flows inside the gob are largely unknown and CFD numerical modeling is a useful technique to gain information about the conditions inside the gob. The focus of this research was to develop CFD models that could be utilized as a predictive tool for hazard analysis. A combination of geo-mechanical modeling and computational fluid dynamics (CFD) modeling was implemented for this research. Information provided by two cooperating mines was analyzed to create the geo-mechanical and CFD models. A validated Mine C, U-Type ventilation model served as the base operating condition of Mine C. This base case model was then modified to create a back return model that demonstrated the effectiveness of a dynamic seal that largely eliminated explosion hazards.

In the CFD model, the gob was treated as a porous medium. This required porosity and permeability distributions to be assigned to the gob. Distributions were determined through geo-mechanical modeling using the FLAC3D software package. Geo-mechanical models were created using the actual mine layout, lithology, caving behavior, and subsidence information provided by the two partner mines. The concept of ‘stepped extraction’ was developed and proved to capture more accurately the effects of an active longwall panel. FLAC models were validated against dynamic subsidence measurements from Mine C. Other validation data included final subsidence profiles from Mines C and E as well as shield loading data from Mine C. The output from FLAC3D modeling was given in terms of volumetric strain and used to determine the porosity distribution in the gob. The initial porosity was determined from bulking factors of the caved material as well as the initial porosity of the immediate roof host rock. The permeability distribution was determined as a function of porosity using the Carman-Kozeny equation.

The program ANSYS Fluent was chosen for the CFD portion of the research. The CFD model was created using mine ventilation system operating characteristics and gas concentration information from
the installed monitoring systems at Mine C. The CFD model for Mine C was validated using gas concentration readings from a tube bundle system and with other mine site measurements. This base case model was then used for parametric studies. The Mine C model included two gob ventilation boreholes and nitrogen injection in a progressively sealed, U-Type ventilation scheme. A modular meshing approach developed by Gilmore (2014) was used to assemble the base U-Type models from a library of geometric mesh modules.

Ventilation related hazards in longwall coal mines include spontaneous combustion and explosive gas zones from methane air mixtures (EGZs). U-type ventilation schemes implementing nitrogen injection were shown to be effective in reducing EGZ volume. An EGZ was located immediately inby the face on the tailgate side. The back return ventilation model resulted in a slight increase in the EGZ volume however, the EGZ was moved several hundred feet inby and away from active working areas. The research on back return arrangements resulted in the following significant findings:

- Utilization of a back return effectively prevents the gob atmosphere from migrating into the face. This pushes EGZs away from the working areas of the longwall face.
- Implementing a back return also sweeps the tailgate corner with fresh air, removing the EGZ hazard directly inby the shields even when nitrogen is not injected. This eliminates the near face EGZ commonly occurring with U-Type ventilation. An EGZ in upper regions of the gob may remain.
- The spontaneous combustion risk is greater when a back return is used over a U-Type ventilation scheme due to increased oxygen ingress.
- Tailgate nitrogen injection is ineffective in back return schemes.
- Nitrogen injected from the headgate side forms a dynamic seal across the gob that moves with the face and effectively separates the fresh air near the face from the methane rich interior of the gob. This greatly reduces the size of the EGZ in the dilution zone between these atmospheres. When a back return is implemented, this dynamic seal becomes complete, extending from the headgate injection point to the tailgate side return. The minimum nitrogen quantity resulting in a dynamic seal was 0.4m³/s injected from the headgate side. The oxygen concentration dropped rapidly and the area beyond the location of the dynamic seal was below spontaneous combustion thresholds.
- Nitrogen injection location studies revealed that injection locations closer to the working face were most effective. The EGZ volume and the amount of oxygen ingress steadily increased as nitrogen injection locations were moved further inby.
- A sealed gob self-inertizes faster if the coal emits methane at higher rates. Mines with low methane emission are more hazardous during sealing since the gob remains in the explosive range for a longer duration.
- Nitrogen injection was shown to reduce panel inertization times during sealing. Nitrogen injection was also shown to eliminate the EGZ that forms in the recovery room when nitrogen injection is not used and the panel is allowed to self-inert through natural processes.
These findings give the coal mining industry a greater understanding of gob gas flow and distribution. It is recognized that every mine is different and even within the same mine conditions may change from panel to panel or within the same panel. Understanding flow patterns and trends of gas concentrations within the gob allows industry to develop hazard mitigation strategies that are pertinent to particular conditions at the mine. The results presented in this dissertation can be used for trend analysis.

An economic analysis was completed on nitrogen injection quantity. The analysis used a cost-benefit approach of net present value cash flow comparisons. The economic model was based on the model of a typical Western US longwall coal mine first developed by Grubb (2008). Nitrogen injection is a significant cost that impacts the net present cash flow of a mining operation. An economic analysis revealed that nitrogen injection had a smaller impact on mine’s net present cash flow than a spontaneous combustion event occurring within the first 10 years of mining. The economic analysis shows that the benefit of nitrogen injection can be significant if a major spontaneous combustion event is prevented.

6.1 Original contribution to the field of mining engineering

The research on nitrogen injection strategies for spontaneous combustion and EGZ hazard mitigation in progressively sealed longwall panels implementing a back return has provided the following original contributions to the field:

- A realistic geomechanical response of the gob in Western Coal mines that was calibrated against mine data including subsidence curves and shield loading measurements. The porosity distribution was determined from the volumetric strain and bulking factor to determine the porosity distribution. The permeability distribution was determined from the Carman-Kozeny equation.
- The concept was developed and proved of a dynamic seal formed in progressively sealed gobs by injecting nitrogen inby the headgate. The formation of a complete dynamic seal at the working level of the gob can only be created by implementing a back return scheme. This concept is a new approach to assessing both the EGZ and spontaneous combustion hazards at the same time. Although a dynamic seal forms in U-Type schemes without back returns it was determined that a complete dynamic seal could not be formed unless a back return was used.
Proving the concept of a back return. The back return removes methane accumulation near the tailgate, directly inby the face, and replaces this region with fresh air. As a result, all EGZ hazards directly adjacent to the face are eliminated.

The porous media distribution in the gob is important to accurately capture the flow patterns in the gob. This is particularly true in progressively sealed panels, where the area of interest is within the first few hundred meters inby the face. The concept of stepped extraction was validated against dynamic subsidence information provided by Mine C. There is a noticeable difference between ‘single step’ extraction and ‘stepped’ extraction, with stepped extraction resulting in a more realistic, asymmetrical permeability distribution in the gob. Previous work in this field resulted in unrealistic geomechanical behavior and the subsidence profiles did not flatten out even along the length of the panel, a distance of over 1,000 meters. Due to these effects, previous researchers had to artificially flatten the resulting permeability and porosity distributions by applying a lower limit to the minimum permeability. This cap affected nearly all of the center of the panel, particularly near the start-up room and will be significant for modeling longwall panels utilizing bleeder ventilation.

Nitrogen injection into the gob has been used in the mining industry for many years, as early as 1981 (Both, 1981), but practical application is still inconclusive in terms of optimum location, quantity and number of injection points. Effective nitrogen injection requires an understanding of the impact of the nitrogen injection strategy on the resulting gob gas distributions. As discussed in the literature review section, numerous other researchers have investigated the effect of nitrogen injection in progressively sealed panels. Worrall (2012) primarily researched U-Type ventilation schemes and concluded that nitrogen injection was an effective measure to mitigate both EGZ and spontaneous combustion hazards. He also determined that nitrogen injection from the headgate is more effective than nitrogen injection from the tailgate. A final conclusion of Worrall was that nitrogen injection reaches a point of diminishing returns. The two critical areas that had not been previously addressed were EGZ hazards and the accumulation of methane behind shields near the tailgate corner.

A back return ventilation arrangement was shown not only to sweep the tailgate corner of methane accumulations but to also remove the EGZ hazard in close proximity to the face. A study was undertaken to determine an appropriate scheme in terms of injection location and quantity for back return ventilated gobs. The concept of a dynamic seal was introduced to determine the effectiveness of
nitrogen injection. It was concluded that a complete dynamic seal can be formed only by using back return schemes.

The findings presented in this dissertation are an important step towards a “Zero Harm” culture by significantly reducing the risk associated with ventilation related hazards.

6.2 Recommendations for future work

The following recommendations for future work falls into two categories. The first category is further investigation to gain insight into the impact of additional ventilation system operational parameters. The second category is the relaxation of assumptions used to create the present models.

Further study should include the following items:

- Nitrogen injection strategy. The research presented in this dissertation investigates the impact of injection location inby the face at the working seam level through progressively constructed seals. Further research should include vertical borehole injection locations, potentially on the headgate side of the panel and near the active face. This scheme could prove beneficial by reducing the EGZ located in upper regions of the gob; a zone unaffected by the nitrogen injection schemes from the working seam level presented in this research. A crucial part of this study would be to determine the technical and economic feasibility of the additional drilling required for nitrogen injection through headgate boreholes.

- Gob vent borehole operational guidelines. In this research, the gob vent boreholes were modeled as constantly exhausting outlets. In practice, the gob vent boreholes are closely monitored and shut off once oxygen or nitrogen concentration rises suggesting that the gob vent boreholes are beginning to pull air from the face ventilation. Simulating the transient response of the gob vent boreholes, for example shutting them off once the methane concentration drops, needs to be examined. Further, operators at Mine C expressed interest in the impact of gob vent borehole location on gob gas distributions.

- Operational guidelines for bleeder ventilated panels. The research discussed in this dissertation focused on progressively sealed panels, specifically panel utilizing a back return. The US mining regulations (CFR Title 30, Part 75) require that mines operate bleeder ventilated panels unless they have shown a high propensity for spontaneous combustion. Research by Gilmore (2014) shows that the EGZ in bleeder panels is much larger and contiguous along the fringes of the gob confirming the phenomenon described by Brune, 2013. Research should focus on ventilation controls that can be used to both control the location and minimize the size of the EGZ. One challenge in bleeder ventilated gobs is that nitrogen injection is not feasible using this method of ventilation.
- Completely eliminating the EGZ hazard. Increasing the amount of nitrogen injection will reduce the oxygen content in the tailgate return. It may be possible to change the location of nitrogen injection, but tailgate injection is ineffective. The EGZs form along oxygen-methane dilution boundaries if insufficient nitrogen is present. Most of these EGZs form in upper regions of the gob. Targeted nitrogen injection in the upper regions of the gob may be successful at eliminating these EGZs. A delivery method could include injection from a borehole drilled on the headgate side or adding injection ports behind the shields themselves. Adding the injection ports behind the shields allows the oxygen to be diluted as it enters the gob and when injected at a sufficient rate may prevent EGZ formation.

The following assumptions should be re-evaluated:

- Impact of changing barometric pressure. The barometric pressure was modeled as a constant value. This simplification cannot be made when studying the impact of a passing storm. The storm results in a falling barometer which can cause the gob to outgas into the working areas. A transient study should be used to determine the impact of fluctuating barometric pressure on gob gas distributions.

- Spontaneous combustion chemical reactions. Spontaneous combustion reactions are not modeled due to the complexity involved in modeling chemical reactions in large scale models. An approach developed by Yuan and Smith (2007) simplifies the reaction to study the formation of “hot zones” but the coal is introduced manually into areas of interest. A validated model for Mine E cannot be completed until spontaneous combustion reactions are incorporated due to lack of methane; the gob atmosphere is primarily carbon dioxide produced from the oxidation of coal.

- Fractured zone porous media distribution. The porous media distribution of the fractured is currently assumed to be constant. A method of estimating the permeability distribution from stress prediction in the gob was developed by Karacan (2005) and should be used to evaluate the impact on gob vent borehole performance.

- Methane desorption model. The boundary condition for methane inlet is currently a uniform release throughout the entire model. In reality some sort of pressure based distribution is expected. The stress distribution mentioned in the previous point could be a starting point. Higher stress values would correspond to further deformation and therefore higher release of methane. This study would have to be completed as a transient study with an equal time step for both the CFD and the geo-mechanical model. Limitations of the geo-mechanical modeling software restrict the feasibility of this study due to the computational time required.

- Work done to date on gob gas research, specifically regarding EGZs, has been limited to studying the location of EGZs and not what happens if an ignition does occur. This research would be beneficial to the mining industry in terms of risk mitigation and event planning to eliminate mining catastrophes related to gas explosions.
REFERENCES CITED


Darcy, H. (1856). Les fontaines publiques de la ville de Dijon: exposition et application... de distribution d'eau... Victor Dalmont.


Mine E. (2013). Site Visit


APPENDIX A FLAC3D Code

MINE C Example

; Gate-Road Sub Assembly Creation -4m by 4m Grids
new ;also try Ubiquitous joint model

;title
;Longwall Gob Compaction Model - NIOSH Research Grant

set fish safe_conversion off

Config zextra 4

;set large

; Pre-Gob-Removal Grids Step

gen zone brick size 90, 150, 28 ...
p0 -450,0,-140 p1 450,0,-140 p2 -450,1500,-140 p3 -450,0,140 group OB_Grid

; DELETE FOR REFINED GATEROAD GRIDS - GOB  (GOB -200 -> 200 (X) & 250 -> 1250 (Y)

group TEMP_1 range x -200 200 y 250 1250 z -20 140

DEL zone range group TEMP_1

; 5m Grids for Overburden

gen zone brick size 80, 200, 12 ...
p0 -200,250,20 p1 200,250,20 p2 -200,1250,20 p3 -200,250,140 group REFINE_5m

gen zone brick size 80, 200, 1 ...
p0 -200,250,-20 p1 200,250,-20 p2 -200,1250,-20 p3 -200,250,-10 group REFINE_5m

gen zone brick size 160, 400, 3 ...
p0 -200,250,-10 p1 200,250,-10 p2 -200,1250,-10 p3 -200,250,20 group REFINE_2_5m

; DELETE FOR REFINED GATEROAD GRIDS - GOB  (GOB -200 -> 200 (X) & 250 -> 1250 (Y)

group TEMP_2 range x -200 200 y 250 1250 z 30 110

DEL zone range group TEMP_2

gen zone brick size 40, 100, 8 ...
p0 -200,250,30 p1 200,250,30 p2 -200,1250,30 p3 -200,250,110 group REFINE_10m
; OB LITHOLOGY

; Liz Original Stratigraphic Column - My Modifications

m mech mohr ;Mudstone

prop b=845.8e6 s=507.5e6 den=2378.74 c=0.4e6 fric= 37.6 dil=10 ; LIZ

; prop b=3333.0e6 s=2000.0e6 den=2378.74 c=3.3e6 fric= 37.6 dil=10.0 ; NIOSH

; Strain Softening for Ground

; FLOOR Dilation

tab 90 0.000 10.0

tab 90 0.001 8.00

tab 90 0.002 6.00

tab 90 0.003 4.00

tab 90 0.004 2.00

tab 90 0.005 0.00

; FLOOR Cohesion

tab 97 0.0000 1.11e06

tab 97 0.0010 1.09e06

tab 97 0.0020 1.07e06

tab 97 0.0030 1.05e06

tab 97 0.0040 1.02e06

tab 97 0.0045 1.01e06

tab 97 0.0050 1.11e05

tab 97 0.0060 8.91e04

tab 97 0.0070 6.68e04

tab 97 0.0080 4.46e04

tab 97 0.0090 2.23e04

tab 97 0.0100 0.0e0

tab 97 0.0120 0.0e0

; UB Joints
; ESSIE joint Data

; VERY WEAK: Cohesion= 0.055 (MPa) Friction Angle= 21
; WEAK: Cohesion= 0.5 (MPa) Friction Angle= 21
; MODERATE: Cohesion= 3.3 (MPa) Friction Angle= 24
; STRONG: Cohesion= 5.5 (MPa) Friction Angle= 26
; VERY STRONG: Cohesion= 10.0 (MPa) Friction Angle= 28

define JOINTS
JCOH= 0.055e06
JFRIC= 21.0
JDIP= 30.0
JDIPDIRECT= 0.0
end

@JOINTS

group OB_1 range x -800 1400 y -2000 2000 z 0 10
m mech ubiquitous range group OB_1
prop b=740.3e6 s=479e6 den=1959.0 c=0.41e6 fric= 41.6 dil=10.0 ;ten =0.412e06
prop jcohesion= @JCOH jfriction= @JFRIC
prop jdip= @JDIP jddirection= @JDIPDIRECT ...

range group OB_1

group OB_2 range x -800 1400 y -2000 2000 z 10 20
m mech ubiquitous range group OB_2
prop b=1722.76e6 s=1267.1e6 den=2397.3 c=1.04e6 fric= 40.9 dil=10.0 ;ten =0.0
prop jcohesion= @JCOH jfriction= @JFRIC
prop jdip= @JDIP jddirection= @JDIPDIRECT ...

range group OB_2

group OB_3 range x -800 1400 y -2000 2000 z 20 30
m mech ubiquitous range group OB_3
prop b=1722.76e6 s=1267.1e6 den=2397.348 c=1.04e6 fric= 40.88 dil=10.0 ten =0.0
prop jcohesion= @JCOH jfriction= @JFRIC
prop jdip= @JDIP jddirection= @JDIPDIRECT ...
range group OB_3
group OB_4 range x -800 1400 y -2000 2000 z 30 40
m mech ubiquitous range group OB_4
prop b=685.87e6 s=514.58e6 den=2550.0 c=0.77e6 fric= 27.03 dil=14.62 ;ten =0.0
prop jcohesion= @JCOH jfriction= @JFRIC
prop jdip= @JDIP jddirection= @JDIPDIRECT ...
range group OB_4
group OB_5 range x -800 1400 y -2000 2000 z 40 50
m mech ubiquitous range group OB_5
prop b=781.828e6 s=510.332e6 den=2447.244 c=0.548e6 fric= 33.372 dil=11.848 ;ten =0.0
prop jcohesion= @JCOH jfriction= @JFRIC
prop jdip= @JDIP jddirection= @JDIPDIRECT ...
range group OB_5
group OB_6 range x -800 1400 y -2000 2000 z 50 60
m mech ubiquitous range group OB_6
prop b=1188.322e6 s=891.548e6 den=2490.8 c=0.942e6 fric= 32.898 dil=12.772 ;ten =0.0
prop jcohesion= @JCOH jfriction= @JFRIC
prop jdip= @JDIP jddirection= @JDIPDIRECT ...
range group OB_6
group OB_7 range x -800 1400 y -2000 2000 z 60 70
m mech ubiquitous range group OB_7
prop b=1188.322e6 s=891.548e6 den=2490.8 c=0.942e6 fric=32.898 dil=12.772 ;ten =0.0
prop jcohesion= @JCOH jfriction= @JFRIC
prop jdip= @JDIP jddirection= @JDIPDIRECT ...
range group OB_7
group OB_8 range x -800 1400 y -2000 2000 z 70 80
m mech ubiquitous range group OB_8
prop b=937.096e6 s=703.064e6 den=2520.4 c=0.856e6 fric=29.964 dil=13.696 ;ten =0.0
prop jcohesion= @JCOH jfriction= @JFRIC
prop jdip= @JDIP jddirection= @JDIPDIRECT ...
range group OB_8

range group OB_9

range group OB_10

range group OB_11

range group OB_12
range group OB_12

group OB_13 range x -800 1400 y -2000 2000 z 120 130

m mech ubiquitous range group OB_13

prop b=1503.52e6 s=1077.2e6 den=2392.696 c=0.88e6 fric=40.06 dil=10.0 ;ten =0.0

prop jcohesion= @JCOH jfriction= @JFRIC

prop jdip= @JDIP jddirection= @JDIPDIRECT ...

range group OB_13

group OB_14 range x -800 1400 y -2000 2000 z 130 140

m mech ubiquitous range group OB_14

prop b=1065.04e6 s=697.4e6 den=2383.392 c=0.56e6 fric=38.42 dil=10.0 ;ten =0.0

prop jcohesion= @JCOH jfriction= @JFRIC

prop jdip= @JDIP jddirection= @JDIPDIRECT ...

range group OB_14

group FLOOR range x -800 1400 y -2000 2000 z -140 0

m mech mohr range group FLOOR; Limestone

;prop b=13333.3e06 s=8000e06 den=2378.74 c=20e06 fric= 36.0 dil=10.0 ten =0.0 range group FLOOR ; Limestone Floor

prop b=845.8e6 s=507.5e6 den=2378.74 c=0.4e6 fric= 37.6 dil=10 ten=0; MUDSTONE

; Strain-Softening Floor - maybe causing instabilities

;m mech strainsoftening range group FLOOR; Limestone

;prop b=13333.3e06 s=8000e06 den=2378.74 c=20e06 fric= 36.0 dil=10.0 ten =0.0 range group FLOOR ; Limestone Floor

;prop dtab 90 ctab 87 range group FLOOR ; Mudstone Floor

; ATTACH COMMAND

attach face range z -130 138 ; To simplify model

attach face range x -450 450

attach face range y 0 1500

;plot create view GROUPS
;plot add zgroup
plot create view ZONE
plot add zone

; SPECIFY THE BC's
fix x range x -449.9 -450.1
fix x range x 449.9 450.1
fix y range y -0.1 0.1
fix y range y 1499.9 1500.1
fix z range z -130.1 -129.9 ; z=0 plane

;INSITU STRESS INSTALLATION
set grav 0.0 -9.81

;INITILIZE DISPLACEMENTS
ini xdis 0 ydis 0 zdisp 0;

;solve  ; Solve Step .......
ini xdis 0 ydis 0 zdisp 0;

;save JUNE-2013-Half_Panel-Model.sav

; GOB Response Curves

;HISTORIES

his n=50

; STRAIN HARDENING Curve Options ..................

; OPTION 13 Salamon's (a=0.925, b=0.44)

tab 13 0.0 0.0
tab 13 0.02 0.04e6
tab 13 0.04 0.09e6
tab 13 0.06 0.15e6
tab 13 0.08 0.21e6
tab 13 0.10 0.27e6
tab 13 0.12 0.35e6
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<td>0.34</td>
<td>3.15e6</td>
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<tr>
<td>Tab 13</td>
<td>0.36</td>
<td>4.16e6</td>
</tr>
<tr>
<td>Tab 13</td>
<td>0.38</td>
<td>5.86e6</td>
</tr>
<tr>
<td>Tab 13</td>
<td>0.40</td>
<td>9.25e6</td>
</tr>
</tbody>
</table>

; HISTORIES TO GATHER DATA
hist add zo szz 15 5 5
hist add gp zdis 15 5 5
history add zo vsi 5 5 5

; EXCAVATION LOOP ............................
def excave
; inputs
step_size = 1000 ;@xy_panel
start=250
panel_end = 1000
panel_height = 10
panel_base = 0
i=0
;Double Yield Gob properties
;_dens =1200
;_bulk_mod = 450e06
;_shear_mod = 600e06
;_cap_pressure_table = 2
;excavation width
panel_width_start = -200
panel_width_end = 200
; front-end calculations
length = panel_end-start
panel_top = panel_base + panel_height
n_steps = length/step_size

; GOB PARAMETERS
PR= 0.25; Poisson's Ratio ; Essie = 0.06
Gravel soil = 0.15-0.35
YM= 8000; Young's Modulus
K_BULK_MOD= (YM/(3*(1-2*PR)))*10^6
G_SHEAR_MOD = (YM/(2*(1+PR)))*10^6
;K_BULK_MOD= 400e06
;G_SHEAR_MOD = 650e06

loop n (1, n_steps)
i=n
y_position = start+(step_size*(i-1))
y_position_end = y_position+(step_size)
command
group newgob range x panel_width_start panel_width_end y y_position y_position_end z panel_base panel_top
mod null range group newgob
step 1
mod doubleyield range group newgob
prop dens 1200 bu @K_BULK_MOD sh @G_SHEAR_MOD fric= 40.0 dil=0.0 ctab 13 ; Sandstone Properties ; effects of friction on final value

prop coh 0 ten 0
endcommand

j= string(i)
command
;set mechanical ratio 1e-05
;solve
;call C:\Users\Jon-Marts\Desktop\gobperm.txt
endcommand
command
group gob range x panel_width_start panel_width_end y y_position y_position_end z panel_base panel_top
endcommand
endloop
end
@excave
;save OB-UB-joints-model_SLICE_SINGLE_STEP
;save OB-UB-joints-model_SLICE_STEPPED
;group gob_info range x 5 15 y 1005 1015 z 0 10
;group surf_info range x 5 15 y 1005 1015 z 130 140
APPENDIX B FLUENT CFD Code (UDFs)

DEFINE_ADJUST(demo_calc,d)

MINE C

DEFINE_ON_DEMAND(VSI_MINE_C_Stepped)

{  
  Domain *d;  Thread *t;  cell_t c;  real x[ND_ND]; /* Fluent location vectors */
  double x_loc_norm, y_loc_norm, x_loc, y_loc;
  double panelwidth=151.4856; /* specified here as half-width */
  double panelength=1000;
  double VSI=0;
  double FUN1, FUN2;
  double maximum_vsi=0.27;
  double blendrange=15, blendrangey=25, mix=0.5;
  double box[7]={0, 100, 200, 0, 190, 700, 1000};
  d = Get_Domain(1);
  /* Assign new panel size from scheme variable define with in FLUENT or use the default sizing above */
  if (RP_Variable_Exists_P("vsi/panel-width")){    /* Returns true if the variable exists */
    panelwidth=( RP_Get_Real("vsi/panel-width") / 2 );
    Message ("Panel width is: %g
",panelwidth*2); } /* else default or manual set above is used */
else{ Message("Panel Width not set. Using default value: %g\n You may set it with TUI Command: (rp-var-define 'vsi/panel-width VALUE 'real #f)\n", panelwidth*2);  }

box[1]=panelwidth-100.0;
box[2]=panelwidth;

if (RP_Variable_Exists_P("vsi/panel-length")){
    panelength=( RP_Get_Real("vsi/panel-length") );
    Message ("Panel length is set to: %g\n reset value using (rpsetvar 'vsi/panel-length VALUE)\n",panelength); }
else{ Message("Panel Length not set. Using default value: %g\n You may set it with TUI Command: (rp-var-define 'vsi/panel-length VALUE 'real #f)\n", panellength); }

box[5]=panelength-300;
box[6]=panelength;

/* Specify a maximum value of VSI for the change porosity from the scheme variable defined in FLUENT */

if (RP_Variable_Exists_P("vsi/maximum-vsi")){
    maximum_vsi=( RP_Get_Real("vsi/maximum-vsi") );
    Message ("The Maximum change in porosity from the maximum-porosity behind the face occurs at the center of the panel and is set to: %g\n",maximum_vsi); } /* else default or manual set above is used */
else{ Message("Maximum change in porosity from the maximum-porosity behind the face occurs at the center of the panel and is NOT set. Using default value: %g\n You may set it with TUI Command: (rp-var-define 'vsi/maximum-vsi VALUE 'real #f)\n", maximum_vsi); }

thread_loop_c(t,d)  {
begin_c_loop(c,t)   {
    C_CENTROID(x,c,t);
    x_loc=fabs(x[0]); /* Center of Panel is Zero and Mirrored */
    y_loc=(panelength+x[1]); /* Shift FLUENT MESH to FLAC3D data Zero point at startup room for equations */
    if( x_loc>panelwidth ){ VSI=0; } /* limit VSI function to only within panel domain sizing */
    else{


if(x_loc < (box[1]-blendrange) ) {
    if (y_loc <0) {VSI=0;}  
    else if (y_loc < box[4]-blendrangey-15){
        x_loc_norm=( -(x_loc-box[1]+20 )/( box[1] ) ); /* NORMALIZE to equation */  
        y_loc_norm=(y_loc/box[4]); 
        VSI
        =SUPER_CRITICAL_MINE_C_STARTUP_CENTER(x_loc_norm, y_loc_norm);
    }

    else if ((y_loc > (box[4]-blendrangey-15) ) && (y_loc < box[4]+blendrangey-15)) {
        mix=0.05; 
        x_loc_norm=( -(x_loc-box[1] )/( box[1] ) ); /* NORMALIZE to equation */  
        y_loc_norm=(y_loc/box[4]); 
        FUN1
        =SUPER_CRITICAL_MINE_C_STARTUP_CENTER(x_loc_norm, y_loc_norm); 
        x_loc_norm=( -x_loc-box[1] )/( box[1] ));
        y_loc_norm=( (y_loc-box[4])/( box[5]-box[4]) ); 
        FUN2 
        =SUPER_CRITICAL_MINE_C_CENTER_PANEL(x_loc_norm, y_loc_norm); 
        VSI=(FUN2*(mix)+FUN1*(1-mix)); }

else if(( y_loc < (box[5]-blendrangey-15 )) )
    & ( y_loc > (box[4]+blendrangey-15) ) ){
        x_loc_norm=( -x_loc-box[1] )/( box[1] )); 
        y_loc_norm=( (y_loc-box[4])/( box[5]-box[4]) ); 
        VSI 
        =SUPER_CRITICAL_MINE_C_CENTER_PANEL(x_loc_norm, y_loc_norm);  
}

else if ((y_loc > (box[5]-blendrangey-15) ) && ( y_loc < box[5]+blendrangey-15)) {
    mix = ((y_loc-box[5]+blendrangey)/(2*blendrangey));
    x_loc_norm=( -(x_loc-box[1] )/( box[1] ));
}
\[ y_{\text{loc norm}} = \frac{(y_{\text{loc}}-box[4])}{(box[5]-box[4])}; \]

\[ \text{FUN1} = \text{SUPER_CRITICAL_MINE_C_CENTER_PANEL}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]

\[ x_{\text{loc norm}} = \frac{(x_{\text{loc}}-box[1]+15)}{box[1]}; \]

\[ y_{\text{loc norm}} = \frac{1-(y_{\text{loc}}-box[5])}{(box[6]-box[5])}; \]

\[ \text{FUN2} = \text{SUPER_CRITICAL_MINE_C_RECOVERY_CENTER}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]

\[ \text{VSI} = (\text{FUN2}*(\text{mix})+\text{FUN1}*(1-\text{mix})); \]

```c
}
else if( (y_{\text{loc}} < box[6]) && (y_{\text{loc}} > (box[5]+\text{blendrangey}-15)) ) { /*
Remained of data points are in the recovery room 600-1000m */

\[ x_{\text{loc norm}} = \frac{(x_{\text{loc}}-box[1]+\text{blendrange}+15)}{box[1]}; \]

\[ y_{\text{loc norm}} = \frac{1-(y_{\text{loc}}-box[5])}{(box[6]-box[5])}; \]

\[ \text{VSI} = \text{SUPER_CRITICAL_MINE_C_RECOVERY_CENTER}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]
}
else { \text{VSI}=0; }
```

```c
}
else if (x_{\text{loc}} <= (box[1]+\text{blendrange})){

\[ \text{mix} = \frac{(x_{\text{loc}}-box[1]+\text{blendrange})}{2*\text{blendrange}}; \]

if (y_{\text{loc}} <0) { \text{VSI}=0; }
else if(y_{\text{loc}} < box[4]){

\[ x_{\text{loc norm}} = \frac{-(x_{\text{loc}}-box[1])}{box[1]}; /* \text{NORMALIZE to equation */

\[ y_{\text{loc norm}} = (y_{\text{loc}}/box[4]); \]

\[ \text{FUN1} = \text{SUPER_CRITICAL_MINE_C_STARTUP_CENTER}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]

\[ x_{\text{loc norm}} = \frac{1-(x_{\text{loc}}-box[1])}{(box[2]-box[1])}; \]

\[ y_{\text{loc norm}} = (y_{\text{loc}}/box[4]); \]

\[ \text{FUN2} = \text{SUPER_CRITICAL_MINE_C_STARTUP_GATERoads}(x_{\text{loc norm}}, y_{\text{loc norm}}); \]

\[ \text{VSI} = (\text{FUN2}*(\text{mix})+\text{FUN1}*(1-\text{mix})); \]

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else if(y_loc <= box[5]){
    x_loc_norm=-(x_loc-box[1])/(box[1]);
    y_loc_norm=(y_loc-box[4])/(box[5]-box[4]);
    FUN1=
    SUPER_CRITICAL_MINE_C_CENTER_PANEL(x_loc_norm, y_loc_norm);
    x_loc_norm=1-(x_loc-box[1])/(box[2]-box[1]);
    y_loc_norm=(y_loc-box[4])/(box[5]-box[4]);
    FUN2=
    SUPER_CRITICAL_MINE_C_CENTER_GATERoads(x_loc_norm, y_loc_norm);
    VSI=(FUN2*(mix)+FUN1*(1-mix));
}
else if (y_loc < box[6]){
    x_loc_norm=(x_loc-(box[1]-blendrange))/(box[1]+blendrange);
    y_loc_norm=(1-(y_loc-box[5])/(box[6]-box[5]));
    FUN1=
    SUPER_CRITICAL_MINE_C_RECOVERY_CENTER(x_loc_norm, y_loc_norm);
    x_loc_norm=1-(x_loc-(box[1]+blendrange))/(box[1]+blendrange);
    y_loc_norm=(1-(y_loc-box[5])/(box[6]-box[5]));
    FUN2=
    SUPER_CRITICAL_MINE_C_RECOVERY_GATERoads(x_loc_norm, y_loc_norm);
    VSI=(FUN2*(mix)+FUN1*(1-mix));
} else { VSI=0; }
}
else{
    if (y_loc <0) { VSI=0;}
    else if( y_loc < box[4]-blendrangey)
    x_loc_norm=1-(x_loc-box[1])/(box[2]-box[1]);
    y_loc_norm=(y_loc/box[4]);
}
VSI =
SUPER_CRITICAL_MINE_C_STARTUP_GATEROADS(x_loc_norm, y_loc_norm); } 
else if((y_loc > (box[4]-blendrangey)) && (y_loc <
box[4]+blendrangey)) {
    mix = ((y_loc-box[4]+blendrangey)/(2*blendrangey));
x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) );
y_loc_norm = (y_loc/box[4]); 
FUN1 =
SUPER_CRITICAL_MINE_C_STARTUP_GATEROADS(x_loc_norm, y_loc_norm);
x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) );
y_loc_norm = ( (y_loc-box[4])/( box[5]-box[4]) );
FUN2 =
SUPER_CRITICAL_MINE_C_CENTER_GATEROADS(x_loc_norm, y_loc_norm);
VSI = (FUN2*(mix)+FUN1*(1-mix));   } 
else if(( y_loc < (box[5]-blendrangey-20 )) && ( y_loc >
(box[4]+blendrangey)) ){
    x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) );
y_loc_norm = ( (y_loc-box[4])/( box[5]-box[4]) );
VSI =
SUPER_CRITICAL_MINE_C_CENTER_GATEROADS(x_loc_norm, y_loc_norm); }
else if((y_loc > (box[5]-blendrangey-20) ) && (y_loc <
box[5]+blendrangey+20)) {
    mix = ((y_loc-box[5]+blendrangey)/(2*blendrangey));
x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) );
y_loc_norm = ( (y_loc-box[4])/( box[5]-box[4]) );
FUN1 =
SUPER_CRITICAL_MINE_C_CENTER_GATEROADS(x_loc_norm, y_loc_norm);
x_loc_norm = ( 1-(x_loc-box[1])/( box[2]-box[1] ) );
y_loc_norm = (1-(y_loc-box[5])/(box[6]-box[5]));
FUN2 =
SUPER_CRITICAL_MINE_C_RECOVERY_GATEROADS(x_loc_norm, y_loc_norm);
VSI = (FUN2*(mix)+FUN1*(1-mix));

else if (y_loc<panelength){
    x_loc_norm=(1-(x_loc-box[1])/(box[2]-box[1]));
    y_loc_norm=(1-(y_loc-box[5])/(box[6]-box[5]));
    VSI = SUPER_CRITICAL_MINE_C_RECOVERY_GATERoads(x_loc_norm, y_loc_norm); }
else {VSI=0;}
}

VSI=(VSI>maximum_vsi)?maximum_vsi:VSI;

C_UDMI(c,t,5) = VSI;
}
end_c_loop(c,t)

Print_Scheme_Variable_Settings();

DEFINE_PROFILE(set_poro_VSI,t,nv)
{
    /* n = (V_v - VSI) / V_t
    where n is porosity (%), V_v is volume of voids (cubic meters),
    vsi is volumetric strain (%), and V_t is total volume (cubic meters). */
    real x[ND_ND]; /* position vector x[0]=x, x[1]=y, x[2]=z */
    double V_v = 0.40000;
    real a=1; /* for a scalar */
    if (RP_Variable_Exists_P("vsi/porosity-scaler")) { /* Returns true if the variable exists */
        a=( RP_Get_Real("vsi/porosity-scaler") );
    }
    if (RP_Variable_Exists_P("vsi_MAXIMUM-porosity")){
V_v=( RP_Get_Real("vsi/maximum-porosity") );

begin_c_loop(c,t) {
    C_CENTROID(x,c,t);
    if(ite<=1){
        cellpor = ( (V_v - C_UDMI(c,t,5))*a ); /* Initial Maximum gob porosity minus the change in porosity (VSI). */
        C_PROFILE(c,t,nv) = (cellpor<0)?0:cellpor; /* 'a' scaler for later use */
        C_UDMI(c,t,1) = (cellpor<0)?0:cellpor; }
    if(ite>1){ C_PROFILE(c,t,nv) = C_UDMI(c,t,1); }
} end_c_loop(c,t) }

DEFINE_PROFILE(set_1poro_VSI,t,nv) { ....... and 2 and 3 .......
{
/* n = (V_v - VSI) /V_t
where n is porosity (%), V_v is volume of voids (cubic meters),
vs is volumetric strain (%), and V_t is total volume (cubic meters). */
real x[ND_ND]; /* position vector x[0]=x, x[1]=y, x[2]=z */
/* double V_t=10.0000 * 10.0000 * 10.0000; 10 meter cubed grid cell in FLAC3D */
cell_t c; real cellpor;
double V_v = 0.40000;
real a=1; /* for a scalar */
if (RP_Variable_Exists_P("vsi/porosity-scaler")) { /* Returns true if the variable exists */
a=( RP_Get_Real("vsi/porosity-scaler") ); }
if (RP_Variable_Exists_P("vsi/maximum-porosity")){
    V_v=( RP_Get_Real("vsi/maximum-porosity") );
} begin_c_loop(c,t) {
    C_CENTROID(x,c,t);
if(ite<=1){
    cellpor = ( (V_v - C_UDMI(c,t,5))*a ); /* Initial Maximum gob porosity minus the change in porosity (VSI). */
    C_PROFILE(c,t,nv) = (cellpor<0)?0:cellpor; /* 'a' scaler for later use */
    C_UDMI(c,t,1) = (cellpor<0)?0:cellpor; }
if(ite>1){ C_PROFILE(c,t,nv) = C_UDMI(c,t,1); }
} end_c_loop(c,t) }
DEFINE_PROFILE(set_perm_1_VSI,t,nv) { ....... and 2 and 3 ......}
{
/** FLUENT allows for an inertial resistance parameter to account for turbulent and transitional flow. Inertial resistance can be found using the following equation ANSYS (2010):
C2 = 3.5 / d * (1-n)/ n^3 
where d is the mean particle diameter (meters) and n is the porosity (%) of the medium. This equation is valid for use in the momentum conservation equation used by Ansys, Inc. in FLUENT. */
real x[ND_ND]; /* position vector x[0]=x, x[1]=y, x[2]=z */
cell_t c; double cellporo; double initial_perm; double cellresist;
double V_v=0.40000000; double a=1; double resist_scaler=1; double maximum_resist=5.000000E6; double minimum_resist=1.45000E5; /* equals 6.91e-6 1/m2 permeability */
if (RP_Variable_Exists_P("vsi/maximum-porosity") ){ /* Get scheme variable and assign it if it exists */
    V_v=( RP_Get_Real("vsi/maximum-porosity") );}
if (RP_Variable_Exists_P("vsi/porosity-scaler") ){
    a=( RP_Get_Real("vsi/porosity-scaler") );}
if (RP_Variable_Exists_P("vsi/resist-scaler") ){
    resist_scaler=( RP_Get_Real("vsi/resist-scaler") );}
if (RP_Variable_Exists_P("vsi/maximum-resist") ){
maximum_resist=( RP_Get_Real("vsi/maximum-resist") );

if (RP_Variable_Exists_P("vsi/minimum-resist") ){
    minimum_resist=( RP_Get_Real("vsi/minimum-resist") );
}

initial_permeability = Initial_Perm();

begin_c_loop(c,t) {
    C_CENTROID(x,c,t);
    
    if(ite<=1){
        cellporo =(( V_v - C_UDMI(c,t,5) )*a<0 )?0:(V_v - C_UDMI(c,t,5) )*a; /* Limit lowest value of porosity to zero */
        cellresist = Cell_Resistance(cellporo, initial_permeability); /* Carmen-Kozeny Relationship */
        /* Limit MAX and MIN resistance */
        if(cellresist < maximum_resist){
            if(cellresist < minimum_resist){ cellresist=minimum_resist; }
        }else{
            cellresist=maximum_resist; }
        C_PROFILE(c,t,nv) = cellresist * resist_scaler; /* Scaler applied to cell resistance */
        C_UDMI(c,t,0) = cellresist * resist_scaler;
    }
    if(ite>1) {
        C_PROFILE(c,t,nv) = C_UDMI(c,t,0); }
} end_c_loop(c,t)

}
real px; real py; real u;
real v; real u1; real v1; real w;
real Y_CH4, Y_O2, Y_N2, MW_CH4, MW_O2, MW_N2, MW_Mix, X_CH4, X_O2;
real explode;
d = Get_Domain(1);
thread_loop_c(t,d) {
    begin_c_loop(c,t) {
        /* Y_X = Mass Fraction of Species X  || X_X = Mole Fraction of Species X */
        Y_CH4=C_YI(c,t,0);
        Y_O2=C_YI(c,t,1);
        Y_N2=1.0-Y_CH4-Y_O2;
        MW_CH4= 28.0134;
        MW_O2= 31.9988;
        MW_N2= 28.0134;
        MW_Mix= 1/(Y_CH4/MW_CH4+Y_O2/MW_O2+Y_N2/MW_N2);
        X_CH4=(Y_CH4*MW_Mix)/MW_CH4; /* X = Mole Fraction of X */
        X_O2=(Y_O2*MW_Mix)/MW_O2;
        px= X_CH4;
        py=X_O2;
        u = 0.8529*px+0.0606; /* Near Explosive to Explosive Slope */
        v=-0.21*px+0.21; /* Upper Explosive Limit */
        u1=0.8864*px+0.0445; /* Near Explosive to Requires Air Slope */
        v1=-1.3929*px+0.195;
        w=-0.11376666666667*px+0.11376666666667;
        /*v1=-1.2647*px+0.1771; Cyan to Yellow Slope Transition */
        /*w=-1.8545*px+0.2095; Continuation of Slope Oxygen Rich to Oxygen Poor */
        /* Explosive Zone - RED */
    }
}

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if (py > u && px > 0.055) {
    explode = 1.0E0;
    C_UDMI(c,t,2) = explode;
}

/* Near Explosive Zone - ORANGE */
else if (py > u1 && px > 0.04) {
    explode = 0.81E0;
    C_UDMI(c,t,2) = explode;
}

/* Fuel Rich Inert - YELLOW */
else if (py < u1 && py > v1 && px > 0.055) {
    explode = 0.66E0;
    C_UDMI(c,t,2) = explode;
}

/* Oxygen Lean Inert - Green A */
else if (py < v1 && px > 0.04) {
    explode = 0.48E0;
    C_UDMI(c,t,2) = explode;
}

/* Oxygen Lean Inert - DARK GREEN */
else if (py < 0.08 && px < 0.04) {
    explode = 0.0E0;
    C_UDMI(c,t,2) = explode;
}

/* Oxygen Lean Inert - Green B */
else if (py < w && px < 0.04) {
    explode = 0.48E0;
}
C_UDMI(c,t,2) = explode;
}

/* Oxygen Rich Inert - CYAN */
else if (py>w) {
    explode = 0.27E0;
    C_UDMI(c,t,2) = explode;
}

/* Explosive Zone - DARK BLUE */
else{
    explode = 2.66E0;
    C_UDMI(c,t,2) = explode;
}

} end_c_loop(c,t) }

________________________________________
|                                       |
|   Explosive Intergral                 |
|   Must use Volume-Integral-report     |
|                                       |
|   STORES in (user-define-memory 3)    |
|            udm-3                      |
----------------------------------------

* /
DEFINE_ON_DEMAND(calc_explosive_integral_gob)
{
    Domain *d; Thread *t; cell_t c;
    d = Get_Domain(1);
    thread_loop_c(t,d) {

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\begin{verbatim}
begin_c_loop(c,t) {
    if (C_UDMI(c,t,2)>0.99e0 && C_UDMI(c,t,2)<1.01){
        /* Assign marker value for cell volume that is explosive */
        C_UDMI(c,t,3)=1.00E0*C_UDMI(c,t,1); } /* Report Volume-Volume-
        Integral udm-3 */
        /* Cell_Volume*Cell_Porosity*1.000e0 = The explosive volume reported */
    } end_c_loop(c,t) 
} DEFINE_ON_DEMAND(calc_explosive_integral)
{
    Domain *d;  Thread *t;  cell_t c;
    d = Get_Domain(1);
    thread_loop_c(t,d){
        begin_c_loop(c,t) {
            if (C_UDMI(c,t,2)>0.99e0 && C_UDMI(c,t,2)<1.01){
                /* Assign marker value for cell volume that is explosive */
                C_UDMI(c,t,3)=1.00E0; } /* Report Volume-Volume-Integral udm-3 */
                /* Cell_Volume*1.000e0 = The explosive volume reported */
            } end_c_loop(c,t) 
        }
    } DEFINE_ON_DEMAND(reset_explosive_integral)
{
    /* Required to execute on transient runs - otherwise explosive volume is additive */
    Domain *d;  Thread *t;  cell_t c;
    d = Get_Domain(1);
    thread_loop_c(t,d) 
}
\end{verbatim}
begin_c_loop(c,t) {
C_UDMI(c,t,3)=0.00E0;
} end_c_loop(c,t) 
} */