

**INFLUENCE OF SCALE ON THE INERTING OF DUST
EXPLOSIONS**

by

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DEDICATION

I would like to dedicate this work to my family; my parents Arun and Kabita, and my younger brother, Anil. Their support, advice and understanding were essential to this endeavor. Thank you all very much.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AIM:	Atlantic Industrial Minerals
ASTM:	American Society for Testing and Materials
BEM:	Bruceton Experimental Mine
CAPT:	Calculated Adiabatic Flame Temperature
CBDC:	Cape Breton Development Corporation
CEA:	Chemical Equilibrium and Applications
D/A:	Digital – to –Analog
EMB:	Experimental Mine Barbara
HV:	High Value
ISO:	International Standards Organization
JANAF:	Joint Army-Navy-Air Force
L/D:	Length-to-Diameter
LLEM:	Lake Lynn Experimental Mine
LOC:	Limiting Oxygen Content (%)
MAP:	Monoammonium Phosphate
MEC:	Minimum Explosible Concentration (g/m ³)
MIC:	Minimum Inerting Concentration (g/m ³)
NASA:	National Aeronautics and Space Administration

NFPA:	National Fire Protection Association
NIOSH:	National Institute of Occupational Safety and Health
NIST:	National Institute of Standards and Technology
PRC:	Pittsburgh Research Center
PRL:	Pittsburgh Research Laboratory
SBC:	Sodium Bicarbonate
SEEP:	Suppressant Enhanced Explosion Parameters
TIC:	Total Incombustible Content (%)
USBM:	United States Bureau of Mines
VDI:	Verein Deutscher Ingenieure

Symbols

(dP/dt) :	rate of pressure rise (bar/s)
$(dP/dt)_m$:	maximum rate of pressure rise (bar/s)
$(dP/dt)_{max}$:	maximum $(dP/dt)_m$ over a wide range of dust mixture concentrations (bar/s)
C_p :	specific heat of combustion products (cal/g °C)
D_w :	arithmetic volume or mass mean diameter (μm)
H :	heat of combustion of volatiles (cal/g)
K_{St} :	size-normalized maximum rate of pressure rise (bar m/s)
P_{ex} :	maximum experimental overpressure (bar(g))

P_{ig} :	overpressure due to the igniter (bar)
P_m :	maximum overpressure due to an explosion (bar(g))
P_{max} :	maximum P_m over a wide range of dust mixture concentrations (bar(g))
R :	universal gas constant (J/K mole)
T :	absolute temperature (K)
β :	β -Factor
H° :	Enthalpy
S° :	Entropy

ABSTRACT

Experiments were performed to compare intermediate-scale (1-m³) and laboratory-scale (20-L) inerting results. In general, laboratory-scale inerting levels were higher than intermediate-scale values. This can be attributed to the use of a strong ignition source to initiate the inerting experiments, which may have overdriven the explosions in the smaller test vessel. Previously reported agreement between the smaller test vessel and full-scale experiments may be due to overdriving in the 20-L chamber, leading to high inerting levels similar to those encountered in full-scale tests due to flame acceleration. Use of weaker ignition sources in the laboratory-scale chamber did produce inerting levels similar to those observed in the intermediate-scale vessel.

A new flammability limit parameter has been defined by J. Going, K. Chatrathi, P. Amyotte and A. G. Dastidar as the Minimum Inerting Concentration (MIC; in units of mass concentration, i.e. g/m³). This is the concentration of inertant required to prevent a dust explosion regardless of fuel concentration. Previous experimental work at Fike Corporation (Blue Springs, MO) in a 1-m³ spherical chamber has shown this flammability limit to exist for coal dust when inerting with monoammonium phosphate, sodium bicarbonate and lime stone. The MIC also existed for cornstarch powder when inerting with sodium bicarbonate. In the current work, inerting experiments on a larger variety of dusts were performed in a spherical 1-m³ chamber and a 20-L Siwek chamber using identical materials. The results show that an MIC can be determined for some materials in both chambers.

Calculated adiabatic flame temperatures (CAFT), along with a selected limit flame temperature for combustion propagation, have been used in determining the flammability envelope for hydrocarbon gases. The current work discusses the use of this methodology to determine the flammability of solid fuel/oxidizer/inertant mixtures based upon previous work by other researchers. Their model has been modified to allow for comparisons between inerting levels determined in a 20-L chamber and a 1-m³ chamber. The results indicate that the 20-L and 1-m³ models can be used to predict the experimental inerting levels of the 1-m³ chamber, with limitations. Ultimately, the utility of this modified CAFT and limit flame temperature model as a predictive/screening tool for inerting level and minimum inerting concentration determination has been demonstrated to perform well at low fuel dust concentrations.

1 GENERAL INTRODUCTION

A dust explosion is a gas/solid dynamic phenomenon where ignition and rapid combustion of a finely divided material, in a confined space, leads to a large pressure effect. The components necessary for dust explosions are often referred to diagrammatically in a dust explosion pentagon comprising: the fuel, the oxidant, the ignition source, the level of confinement and the dispersion of the fuel into the oxidant.

Dust explosion mitigation strategies revolve around eliminating at least one of the five factors. One such strategy is to use a non-combustible inert material as a thermal heat sink to quench the propagation of the explosion. If the inert material is injected into the operating unit to mitigate an explosion after it has already started, the strategy is called suppression. If the non-combustible material is intimately premixed with the fuel, the strategy is called inerting. Both methods are related, only differing as to when the non-reactive heat sink is introduced into the system.

In the author's previous work (Dastidar, 1996 and Dastidar *et al.*, 1997) on the inerting of coal dust explosions using rock dust, small-scale 20-L experiments closely matched inerting levels determined in large mine-scale experiments. Building upon these results, the author chose to examine how well small-scale inerting levels determined in the 20-L Siwek chamber (Kühner AG, Basel, Switzerland) would match inerting levels determined in an intermediate-scale, spherical, 1-m³ vessel (Fike Corporation, Blue Springs, MO). The issue that arises is the utility of using the small-scale chamber to produce inerting levels that are similar to both intermediate-scale and mine-scale inerting levels. The latter has been demonstrated to be possible from previous research work; the former is the objective of this thesis.

The 1-m³ volume is an important size since it is often referred to in standard test procedures (e.g. ASTM and ISO) to determine dust explosion parameters of maximum overpressure, maximum rate of pressure rise and minimum explosible concentration and also to determine dust explosion suppression requirements. It is not as susceptible to wall quenching effects and ignition source overdriving influences as is the 20-L volume. However, the physical size of the 1-m³ chamber and the quantity of dust required to

establish explosion parameters makes it costly and time-consuming to use. This is especially true when many experiments are required to establish explosion inerting levels for a mitigation strategy. If the smaller spherical 20-L chamber could produce similar test results to the 1-m³ chamber, operational economies could be realized. The question remains as to whether the 20-L inerting levels match 1-m³ inerting levels, and under what specific conditions.

Inerting level tests on coal dust and cornstarch powder using monoammonium phosphate, sodium bicarbonate and limestone as inertants were conducted at Fike Corporation (Blue Springs, MO) demonstrated a fuel-dust concentration dependence on the inerting level (unpublished). The researchers found that larger concentrations of fuel require less inert matter to prevent an explosion, in a fixed test volume, than relatively moderate fuel concentration levels. This observation paralleled results obtained by the author's previous work (Dastidar, 1996 and Dastidar *et al.*, 1997) with coal dust explosion inerting. The researchers at Fike Corporation determined that by plotting explosible and non-explosible solid particulate fuel/inertant mixtures, an inerting envelope, similar to the inerting envelope for flammable gases, can be formed. The envelope is formed by drawing a trend line through a series of points interpolated by averaging the highest inertant concentration tested that produced an explosion with the lowest inertant concentration tested that did not produce an explosion for a given fuel concentration. The "nose" of this envelope represents the minimum inerting concentration, MIC. This is the minimum quantity of inertant required to mitigate a dust explosion independent of the fuel concentration (i.e. the least amount of inertant required to mitigate an explosion at any fuel concentration). The MIC can then be used as an important part of a dust explosion mitigation/suppression strategy. Therefore, the current work also focuses on ascertaining if the MIC exists for other materials in the 1-m³ chamber and if the inerting envelope (and MIC) can be observed in the 20-L chamber.

MIC determination, if possible, in the 20-L volume would have beneficial economic advantages. It would minimize both the time required to establish an inerting envelope as well as the quantity of material required for testing. Additional reductions of time and material may also be achieved if the explosible concentrations of fuel/inertant could be

estimated before testing began. The estimation may be possible with the use of a computer model as a predictive tool for inerting level determination. Models based on the use of Calculated Adiabatic Flame Temperatures (CAFT) and a limit flame temperature criterion have been successful in predicting gaseous fuel explosion inerting (Melhem, 1997 and Mashuga and Crowl, 1999). Hertzberg *et al.* (1984, 1986) adapted this CAFT modeling approach for use with dust explosion inerting. In this thesis a computer model, based on modifications of the work by Hertzberg *et al.* (1984, 1986), has been constructed to be used as a predictive tool for dust explosion inerting.

The questions to be answered in this thesis are:

1. "Can inerting envelopes be measured in the 1-m³ chamber for other types of dusts besides coal dust and cornstarch powder?"
2. "Will small-scale (20 L) inerting levels match intermediate-scale (1 m³) inerting levels, and under what test conditions will the small-scale and intermediate-scale inerting levels come to agreement?"
3. "Can inerting envelopes be measured in the small-scale chamber?"
4. "Since it has been demonstrated that small-scale inerting levels agree with mine-scale values, will intermediate-scale inerting levels agree with mine-scale results?"
5. "Can a model be developed to act as a predictive/screening tool to assist in inerting level estimation and thereby reduce the number of experiments that need to be performed?"

This thesis is comprised of five published peer-reviewed journal papers. The thesis sections and their associated publication(s) are listed in Table 1.1. The right-most column of Table 1.1 states the primary objective of each section/paper. The first section listed in the table focuses on the inerting levels and subsequent MIC's determined in the 1-m³ chamber. The second section focuses on the inerting levels and MIC's determined in the

20-L chamber and their relationship to levels determined in the 1-m³ chamber. The third section covers coal dust inerting with rock dust in the 1-m³ and 20-L chambers, examining parameters such as ignition source strength and inertant particle size.

Table I.1: Thesis sections and their respective publications.

Thesis Section	Conference Paper	Journal Paper	Section Objectives
2 Dust Explosion Inerting In An Intermediate-Scale 1-m ³ Spherical Chamber	A. G. Dastidar, P. R. Amyotte, J. Goings and K. Chatrathi, "Flammability limits of dusts - minimum inerting concentrations" Paper No. 5b, 32 nd Annual Loss Prevention Symposium of the AIChE Spring National Meeting, March 8 – 12, 1998	A. G. Dastidar, P. R. Amyotte, J. Goings and K. Chatrathi, "Flammability limits of dusts - minimum inerting concentrations", Process Safety Progress, May 20, 1999	To establish the presence of an inerting envelope and MIC for a variety of dust types in the 1-m ³ spherical chamber.
3 Dust Explosion Inerting In A Small-Scale 20-L Spherical Chamber	-	A. Dastidar and P. Amyotte, "Determination of minimum inerting concentrations for combustible dusts in a laboratory-scale chamber", Trans IChemE, Process Safety and Environmental Protection, vol. 80, Part B, pp. 287-297, 2002.	To study the influence of vessel volume and ignition source strength on the formation of an inerting envelope, and the presence of an MIC, for a variety of dust types. Comparisons to be made with 1-m ³ results.
4 Comparison Of Coal Dust Inerting In An Intermediate-Scale 1-m ³ Spherical Chamber And A Small-Scale 20-L Spherical Chamber	-	A. G. Dastidar, P. R. Amyotte, J. Goings and K. Chatrathi, "Inerting of coal dust explosions in laboratory- and intermediate-scale chambers", Fuel, vol. 80, pp. 1593-1602, 2001.	To compare the inerting utility of rock dust in the 1-m ³ chamber with previous work performed at the small- and mine-scale volumes.
5 A Calculated Adiabatic Flame Temperature Model For The Prediction Of Dust Explosion Inerting Levels	-	A. Dastidar and P. Amyotte, "Using calculated adiabatic flame temperatures to determine dust explosion inerting requirements", Trans IChemE, Process Safety and Environmental Protection, vol. 82, Part B, pp. 142-155, 2004	To develop a model to be used as a predictive tool to assist in the construction of inerting envelopes for various fuel/inertant dust mixtures.
8 Appendix A - Scaling Of Dust Explosion Inerting	A. G. Dastidar, P. R. Amyotte, J. Goings and K. Chatrathi, "Scaling of dust explosion inerting" 8 th International Colloquium on Dust Explosions, Schaumburg, Illinois, September 21 – 25, 1998.	A. G. Dastidar, P. R. Amyotte, J. Goings and K. Chatrathi, "Scaling of dust explosion inerting", Archivum Combustionis, vol. 18, no. 1 – 4, 1998.	To compare rock dust inerting in the 1-m ³ chamber to small- and mine-scale work. To establish the presence of an inerting envelope / MIC in the 1-m ³ and 20-L chambers for various other dusts.

The fourth section examines the utility of using a modified calculated adiabatic flame temperature model as a predictive/screening tool for dust explosion mitigation. The final section in Table 1.1, covered in Appendix A, is a paper which expands on the 1-m³ chamber tests (section 2) with preliminary analysis of the material covered in sections 3 and 4.

A general conclusion is presented in section 6; it unifies the concluding remarks in each of the published journal papers. Section 7 discusses possible future work that may be pursued based on the results and analysis of the current study. The experimental data are presented in tabular form in Appendices B, C and D (sections 10, 11 and 12, respectively).

While the papers presented in the various sections of this thesis are multi-authored works, the author of this thesis is the primary author of all the publications presented here. As such he has been responsible for the formulation, execution and data analysis of the research project presented in these five peer-reviewed journal papers.

1.1 REFERENCES

Dastidar, A.G., (1996) "Rock dust inerting of coal dust explosions in a 20-L Siwek explosion chamber", M.A.Sc. Thesis, Technical University of Nova Scotia, Canada.

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Hertzberg, M., Zlochower, I.A., and Cashdollar, K.L. (1986) "Volatility model for coal dust flame propagation and extinguishment", Twenty-First Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, pp. 325-333.

Mashuga, C.V. and Crowl, D.A., (1999) "Flammability zone prediction using calculated adiabatic flame temperatures" *Process Safety Progress*, vol. 18, no. 3, pp. 127-134.

Melhem, G.A., (1997) "A detailed method for estimating mixture flammability limits using chemical equilibrium", *Process Safety Progress*, vol. 16, no. 4, pp. 203-218.

2 DUST EXPLOSION INERTING IN AN INTERMEDIATE-SCALE 1-M³ SPHERICAL CHAMBER

This section was originally presented as Paper No. 5b "*Flammability limits of dusts - minimum inerting concentrations*" at the 32nd Ann. Loss Prevention Symposium of the AIChE Spring National Meeting, March 8 – 12, 1998. The authors are A. G. Dastidar, P. R. Amyotte, J. Going and K. Chatrathi.

The conference paper was later published as:

A. G. Dastidar, P. R. Amyotte, J. Going and K. Chatrathi, "*Flammability limits of dusts - minimum inerting concentrations*", **Process Safety Progress**, May 20, 1999*. The text and figures in this section are identical to that of the published paper with the exception that section numbers have been added, and figure and table numbers have been changed, to reflect the thesis format.

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2.1 ABSTRACT

A new flammability limit parameter has been defined as the Minimum Inerting Concentration (MIC). This is the concentration of inertant required to prevent a dust explosion regardless of fuel concentration. Previous experimental work at Fike in a 1-m³ spherical chamber has shown this flammability limit to exist for pulverized coal dust and cornstarch. In the current work, inerting experiments with aluminum, anthraquinone and polyethylene dusts as fuels were performed, using monoammonium phosphate and sodium bicarbonate as inertants. The results show that an MIC exists only for anthraquinone inerted with sodium bicarbonate. The other combustible dust and inertant mixtures did not show a definitive MIC, although they did show a strong dependence between inerting level and suspended fuel concentration. As the fuel concentration increased, the amount of inertant required to prevent an explosion decreased.

Even though a definitive MIC was not found for most of the dusts an effective MIC can be estimated from the data. The use of MIC data can aid in the design of explosion suppression schemes.

2.2 INTRODUCTION

Dust explosions are a serious hazard in the process industries. Suppressants are widely used to provide protection against such explosions. For suppression to be effective, it is important to determine the amount of inertant required to prevent an explosion of the dust at any concentration. Inerting concentrations can be determined by performing suppression tests with laboratory-scale equipment or with large- or full-scale equipment. Laboratory-scale tests are often done due to the cost and effort required for full-scale testing.

An additional flammability limit parameter is defined for inerting dust clouds with particulate material. This new parameter is called the Minimum Inerting Concentration (MIC). Minimum inerting concentration is the lowest inert dust concentration above which a dust explosion is not possible for any fuel concentration. The MIC can be determined by measuring the full flammability curve for the fuel-air-inert dust mixture. The approach differs from suppression testing in that the fuel and inertant are pre-mixed and collectively injected into the test vessel.

Tests were performed using the Fike 1-m³ chamber with three different dusts: aluminum, anthraquinone, and polyethylene. The inertants used were monoammonium phosphate and sodium bicarbonate, which have been previously shown to be effective explosion suppressants.

The use of MIC in the design of explosion suppression systems for industrial equipment and chemical isolation barriers in pipes is described. Suppression and isolation designs having inert agent concentrations below the MIC will have the possibility of allowing dust explosions to occur. Therefore, the MIC provides guidance for the safe design of suppression and chemical barrier systems.

2.3 BACKGROUND

The ignition sequence of a dust cloud due to a spark ignition source described by van Larr and Zeeuwen (1985) can also be used for pyrotechnic ignition. Spark breakdown (discharge of the ignitor) results in the ignition of an initial dust/air kernel. This only

occurs if the ignition source produces enough energy fast enough to heat up the dust/air kernel to its ignition temperature. Once ignited, this kernel then acts as the ignition source for the dust surrounding it. The role of an inertant, such as limestone, is to absorb the energy from the ignition source or the primary kernel so that flame propagation cannot occur. Hertzberg *et al.* (1984) argue that inertants can act “thermally” and “chemically”. A “thermal” inertant is one that absorbs heat energy from the flame and prevents propagation. A “chemical” inertant, the authors explain, is one that devolatilizes in the flame zone, with the gases given off inhibiting flame propagation. These gases inert the combustion process by acting as a chain terminator of kinetic mechanisms or by diluting the concentration of gaseous fuel in the combustion zone below the lower flammability limit. Monoammonium phosphate and sodium bicarbonate both behave chemically to some extent.

Previous work done by Dastidar *et al.* (1997) has shown that there is a strong interdependence of the relative amount of premixed inertant required to prevent an explosion and the fuel concentration. The authors report from tests of Pittsburgh and Pocahontas pulverized coals that fuel concentrations near stoichiometric volatile-air mixtures required more limestone to prevent an explosion than higher fuel concentrations. These stoichiometric volatile-air mixtures represent the fuel concentration that produces the maximum explosion overpressure. At volatile-air ratios in excess of stoichiometric there is insufficient oxygen for complete combustion, and the unreacted material acts as a thermal sink, helping to inert the explosion. As a result, a decrease in overpressure is observed. For inerting work this implies that at high fuel concentrations the excess fuel dust acts to increase the effective thermal sink in the dust mixture. Since the fuel aids the inertant there is less inertant needed to prevent an explosion.

The same point was argued by Mintz (1993): by increasing the concentration of fuel in a fixed volume chamber, a very dense dust cloud is formed. In such a cloud, when a fuel particle burns, all the oxygen in its immediate vicinity is consumed in the reaction zone. This, however, will also consume the oxygen that would be required by the neighboring fuel particle for combustion. The transient nature of the combustion propagation wave also means that there is insufficient time for oxygen to be transported to the particle in a

dense dust cloud. This implies that even though there may be sufficient oxygen for combustion globally, there is not enough oxygen in the local vicinity. As a result, the neighboring particle does not burn. This unburned particle then acts as a heat sink reducing the flame temperature and the explosion overpressure. By adding an inertant to the dust mixture, a very dense dust cloud is formed at low fuel concentrations thereby hindering the transport of oxygen to the fuel particle in time for combustion to occur, as well as acting as a thermal sink.

Inerting experiments at Fike have shown a similar concentration dependence on explosion inerting. By plotting the data as fuel and inertant concentrations, the results form an inerting envelope very similar to a flammability envelope. Figures 2.1 and 2.2 show the inerting envelope for Pittsburgh pulverized coal and cornstarch, respectively. The data points represent the explosibility limit of the fuel-inertant mixture. The area to the left of the curve represents the explosible area. In this area there is insufficient inertant to prevent an explosion. The area to the right of the curve represents the nonexplosible area; here there is sufficient inertant to prevent an explosion. The “nose” of the envelope represents the least amount of inertant that would prevent an explosion regardless of fuel concentration.

If this trend is observed for other dusts it could be a useful tool from which adequate protection measures can be implemented. Since at any given time it is very difficult to determine the actual suspended dust concentration in process equipment, or even the potential suspended dust concentration from a process upset, estimates are made in designing explosion protection equipment. One of these estimates is to take the worst case scenario and perform inerting experiments at the fuel concentration that produces the highest overpressure. This results in a relative amount of inertant required to prevent an

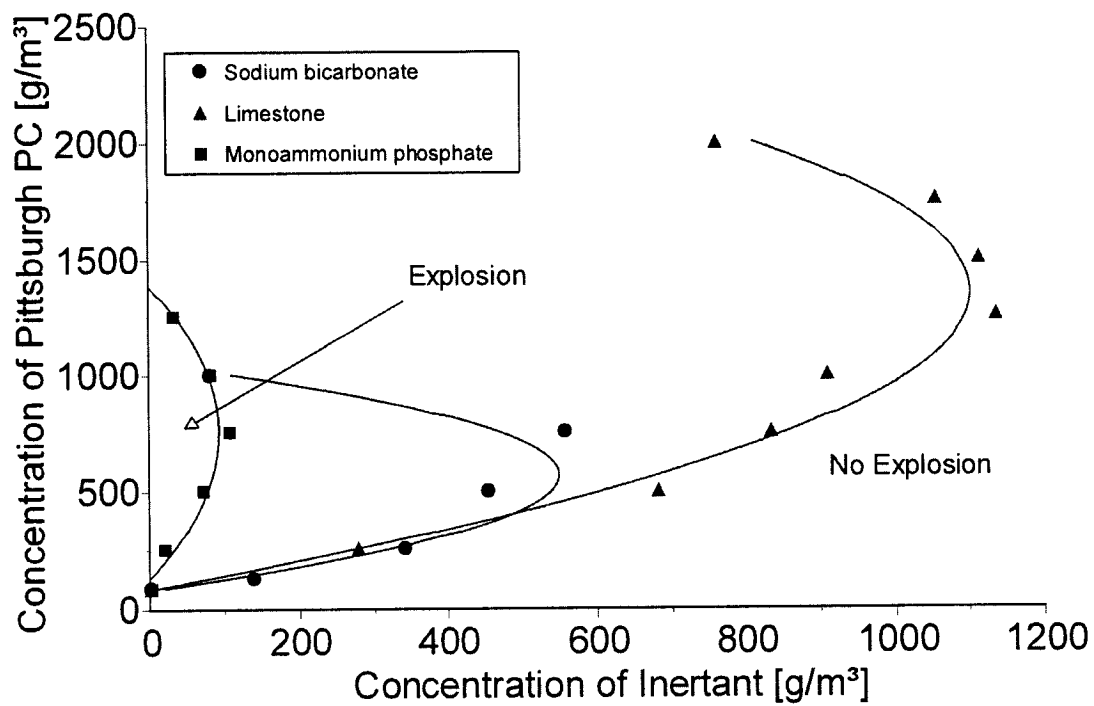


Figure 2.1: Inerting envelope for Pittsburgh pulverized coal dust with sodium bicarbonate, monoammonium phosphate and limestone as inertants.

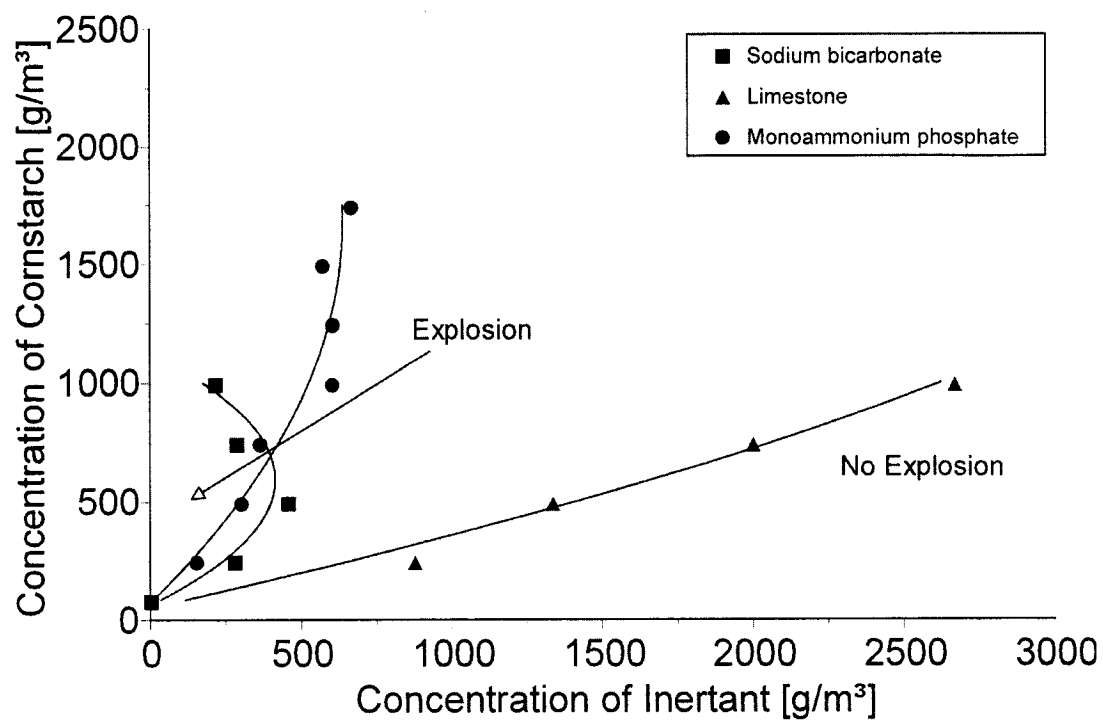


Figure 2.2: Inerting envelope for cornstarch dust with sodium bicarbonate, monoammonium phosphate and limestone as inertants.

explosion. The inerting level cannot be used as an absolute concentration of inertant because higher fuel concentrations would require greater amounts of inert material to prevent an explosion (even though the relative concentration may be less). If the inerting level was to be maintained as a constant ratio, large quantities of inertant would be required at high fuel concentrations. While this may guaranty safety, it poses certain equipment design problems. Suppression devices have to be very large and complicated to be able to introduce such large quantities into the process unit, and the process units themselves have to be designed to accommodate these larger suppression devices.

If, however, an MIC were to exist for a dust, suppression strategies could be designed to introduce a fixed concentration of inertant. A fixed number of high rate discharge containers could be attached to a process unit giving a fixed concentration of inertant. At both low and high fuel concentrations there would be enough inertant to prevent an explosion. So if the concentration of explosible dust were to increase or decrease in the unit, there would always be sufficient inertant to suppress an explosion.

A key point which must be made is that the MIC is an ignition limit, not a suppression limit. This is due to the fact that the inert matter is premixed with the fuel when injected into the test vessel. This intimate contact between the fuel and inertant represents an ideal case. For suppression there may be losses in inertant effectiveness due to the type of dispersion from the discharge canister and incomplete mixing between the inertant and the fuel.

2.4 EXPERIMENTAL

The Fike 1-m³ vessel is a spherical explosion chamber designed to gather explosion severity and explosion protection testing data. A schematic of the apparatus is shown in Figure 2.3. For inerting tests, both combustible dust and inert solid are premixed and then introduced into the vessel. The vessel is made of two 122-cm internal diameter, 0.95-cm thick carbon steel hemispherical sections that can be separated to allow access to the interior. These two halves of the sphere are connected by twelve 51-mm diameter bolts. The vessel has a design pressure of 21 bar (g).

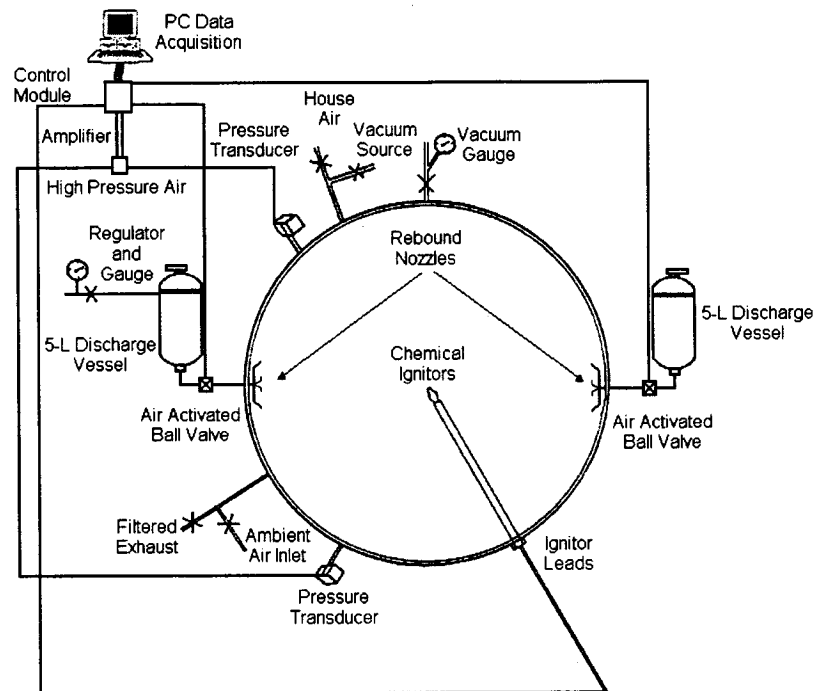


Figure 2.3: Fike 1-m³ vessel.

The dust injection system consists of two 5-L discharge cylinders, each with a ball valve and a Kühner type rebound nozzle for dust dispersion. The outlets on the discharge cylinders and ball valves are 19 mm in diameter. To create a combustible dust cloud in the 1-m³ chamber, a weighed amount of premixed dust and inertant mixture is placed equally into both 5-L cylinders. The 5-L discharge cylinders are pressurized to 19.3 bar(g) each, and the 1-m³ vessel is partially evacuated to 0.88 bar for the dust explosion to occur at atmospheric pressure. The ball valves between the discharge cylinders and the rebound nozzles are opened by using a pneumatic actuator. The air and the dust in the discharge cylinder enter the 1-m³ vessel through the rebound nozzles to create the dust cloud.

The dust explosions are initiated with two chemical ignitors triggered 0.7 s after the activation of the ball valve. The chemical ignitors are manufactured by Sobbe and contain 40% zirconium, 30% barium nitrate and 30% barium peroxide. Each ignitor has 1.2 grams of this mixture and has a stored energy of 5 kJ. The energy is released in about 10 ms. The discharge of ignitors by themselves will cause the pressure to rise by 11 mbar in the 1-m³ chamber.

Two variable reluctance pressure transducers manufactured by Validyne (model DP 215) are used to monitor the progress of the explosions. The transducers in combination with their amplifier electronics have a sufficiently fast response time to provide pressure measurements with a 1 ms resolution. A Metrabyte data acquisition board is used in conjunction with a personal computer to gather the pressure data as a function of time and to control the experiments. Two D/A channels on the data acquisition board are used to activate the ball valves and to initiate the chemical ignitors. Software programming allows control of the delay time between activation of the valves and ignition. It also allows the conversion of the analogue signals into absolute pressure measurements.

Previously, the 1-m³ chamber had only one discharge chamber and dispersion ring. The dispersion time and turbulence level were comparable to those in the European 1-m³ chambers (1989). This is the turbulence level in ASTM Standard E1226, ISO Standard 6184/1, NFPA Guide 68, and VDI Standard 3673 to determine the maximum rate of

pressure rise to determine vent sizes. However, since the nature of inerting experiments requires greater quantities of material (dust and inertant) to be injected into the explosion chamber, the apparatus has been modified to use two dispersion chambers. The ignition delay time has been increased from 0.55 s to 0.7 s and the discharge chamber pressurization has been decreased from 32 bar(g) to 19.3 bar(g) to maintain similar turbulence levels. This procedure is recommended by Bartknecht (1989).

The dusts used in the current tests were aluminum, anthraquinone and polyethylene as fuels, and monoammonium phosphate and sodium bicarbonate as inertants. The choice of fuels was made to represent materials commonly used in the process industries: a metal dust, a chemical intermediate for an organic dye and a typical polymer. The inertants, monoammonium phosphate and sodium bicarbonate, are commonly used suppressants in the explosion protection industry. The particle size of the dusts are given in Table 2.1.

The explosion parameters (overpressure and rate of pressure rise) of the pure fuel dust were determined as a function of concentration. This was achieved by varying the amount of dust placed in the 5-L discharge chambers. The effect of inertant was then determined for each fuel concentration by measuring the explosion parameters as inertant was added to the mixture. The mixture of inertant and fuel was then placed into the two discharge chambers in equal quantities. The criterion used for an explosion was an overpressure of 2 bar(a).

Table 2.1: Table of particle sizes of fuel and inertant dusts used.

Dust	< 100 μm [wt%]	< 25 μm [wt%]	Volume Mean Diameter D_w [μm]
Aluminum	90	50	17
Anthraquinone	92	32	46
Polyethylene	83	17	64
Monoammonium Phosphate	83	18	62
Sodium Bicarbonate	97	32	37

2.5 RESULTS AND DISCUSSION

Figures 2.4 and 2.5 show results of aluminum dust explosion overpressure measurements. Both figures show the overpressure as a function of concentration of pure aluminum, the optimum being between 750 - 1000 g/m³.

From Figures 2.4 and 2.5 it is apparent that as fuel concentration increases, the percent inertant required to prevent an explosion decreases. In the case of sodium bicarbonate as the inertant, the explosion was prevented with an inertant concentration between 55 and 60 % for fuel concentrations below 750 g/m³, and between 50 and 55 % for higher fuel concentrations. With monoammonium phosphate, 60 to 65 % inertant is required to prevent an explosion at concentrations below 1000 g/m³, and 55 to 60% is required for higher concentrations; for the highest concentration tested (2500 g/m³), 50 to 55 % inertant was required. Sodium bicarbonate required slightly less material to inert an explosion than monoammonium phosphate.

It is important to note that while the percent inertant in the mixture required to prevent an explosion decreased, the absolute mass of inertant required to prevent an explosion continued to increase. As a result no true MIC was observed for the inerting of aluminum with sodium bicarbonate or monoammonium phosphate at the concentrations tested. This can be seen in Figure 2.6 where the mass of fuel is plotted against the estimated mass of inertant required to prevent an explosion. The estimated mass was determined by calculating the median concentration between the lowest amount of inertant that did not produce an explosion and the lowest amount of inertant that did produce an explosion. However, the observation that there is a decrease in the relative inertant concentration may mean that the inerting envelope is very broad and the MIC exists at a concentration that has not been tested.

A phenomenon observed in the inerting of aluminum was that if insufficient inertant is used in the fuel/inertant mixture, the explosion overpressure is enhanced to levels greater than that for the pure dust. This phenomenon has been termed SEEP (Suppressant Enhanced Explosion Parameter). It can be attributed to decomposition of the inertant by

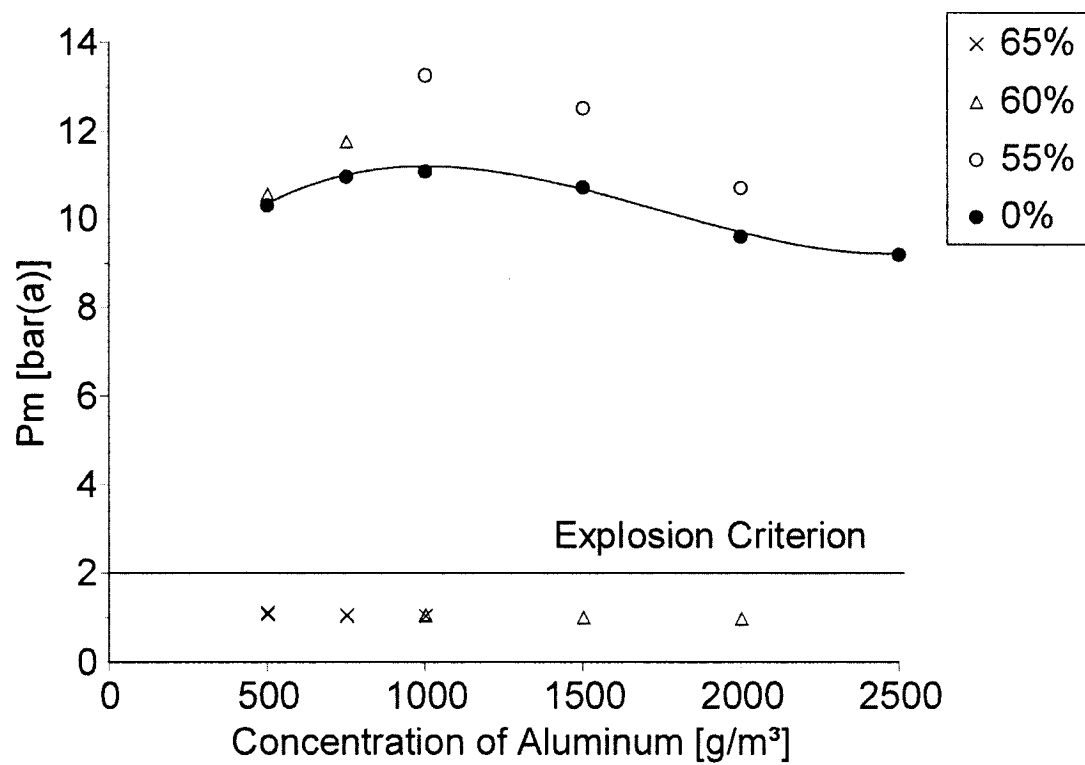


Figure 2.4: Explosion overpressure plotted against aluminum concentration for different amounts of monoammonium phosphate in mixture.

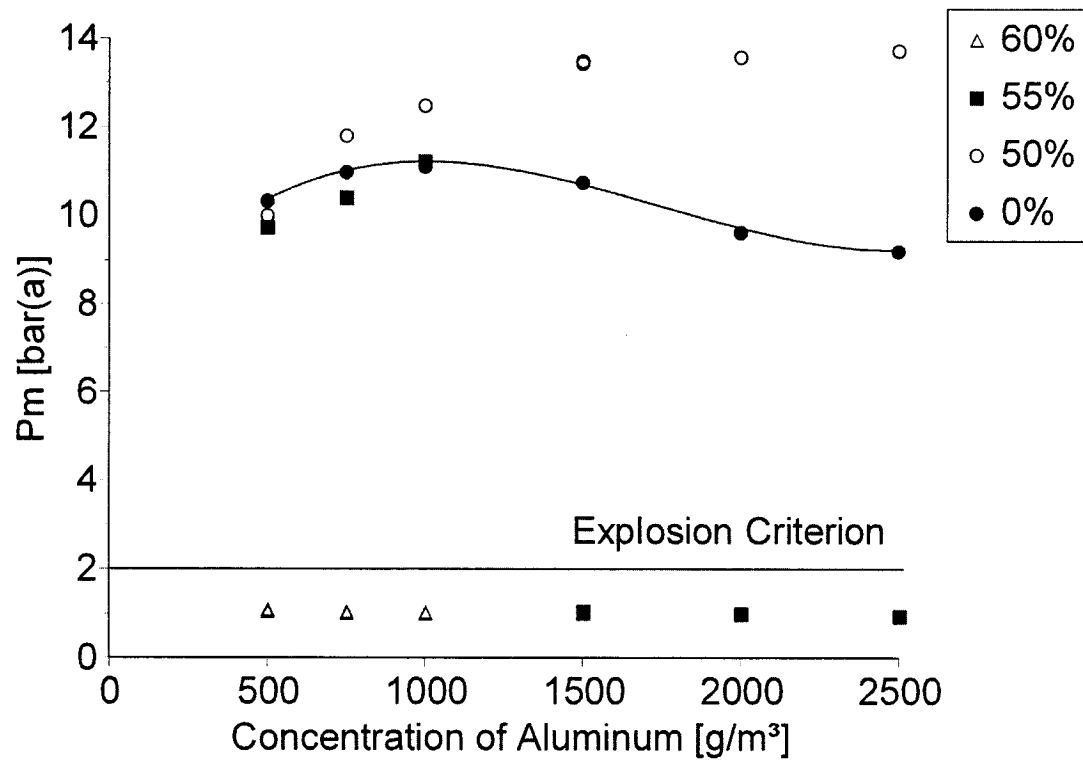


Figure 2.5: Explosion overpressure plotted against aluminum concentration for different amounts of sodium bicarbonate in mixture.

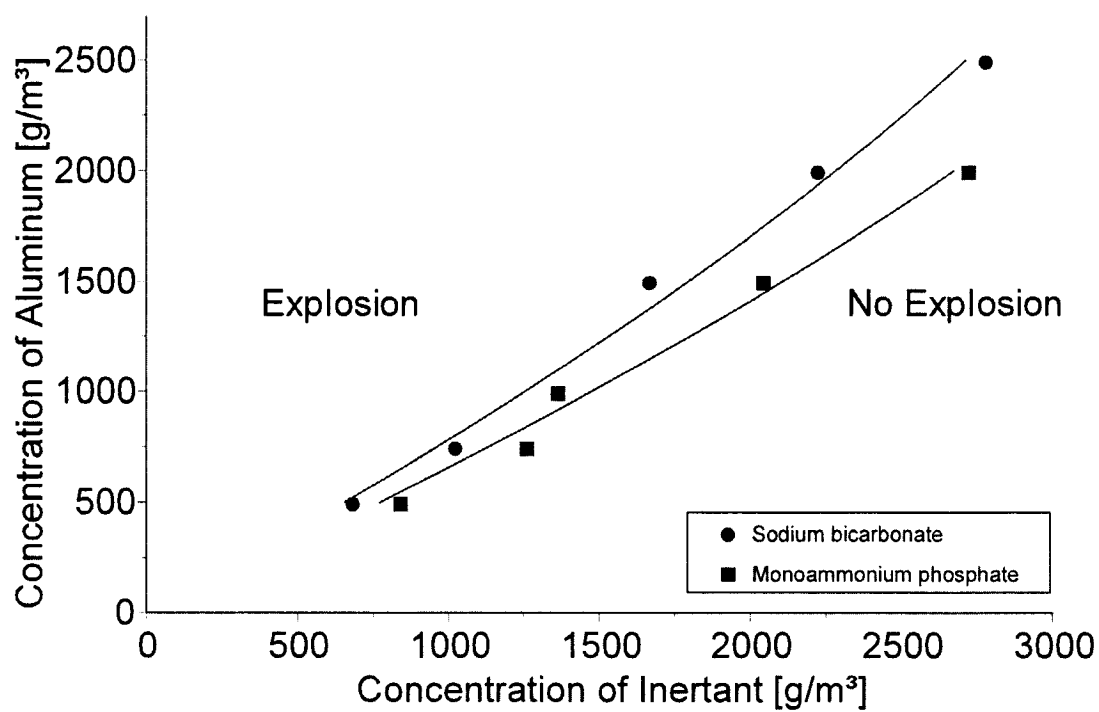


Figure 2.6: Comparison of monoammonium phosphate and sodium bicarbonate inerting curves for aluminum dust.

heat from the combustion of the aluminum. In the case of sodium bicarbonate, carbon dioxide is produced and for monoammonium phosphate, ammonia and hydrogen, both flammable gases, are produced. This raises a concern for the inerting of hot burning metal dusts. If insufficient suppressant is present, this could lead to greater dangers than if no suppressant were used.

Figures 2.7 and 2.8 show results of anthraquinone dust explosion overpressure measurements. Both figures show the overpressure as a function of concentration of pure anthraquinone, the optimum being at 500 g/m³.

Both Figures 2.7 and 2.8 show a trend similar to that seen in the experiments for aluminum: as fuel concentration increases, the percent inertant required to prevent an explosion decreases. For monoammonium phosphate, 55 to 60 % inertant is required to prevent an explosion at concentrations below 750 g/m³, and 50 to 55% inertant is required for higher concentrations. This trend seems to remain constant for the fuel concentration range tested. The percent inertant may decrease if fuel concentration is increased further. With sodium bicarbonate as the inertant, the explosion was prevented with an inertant concentration between 75 and 80 % for low fuel concentrations. This suppression level steadily drops to between 60 and 65% at 1000 g/m³, showing a significant dependence of the inerting level on fuel concentration.

Figure 2.9 is obtained if the inerting results are plotted in a similar manner as the aluminum results. Here, the concentration of fuel is plotted against the concentration of inertant. It is apparent that inerting anthraquinone with monoammonium phosphate does not result in an MIC within the range of fuel concentrations tested. However, the inerting results with sodium bicarbonate clearly show an MIC occurring at about 1700 g/m³ of inertant. It should also be noted that monoammonium phosphate required less material to inert an explosion than sodium bicarbonate.

Figures 2.10 and 2.11 show results of polyethylene dust explosion overpressure measurements. As in the previous figures, the overpressure of the pure dust as a function of concentration is shown, the optimum being at 250 g/m³.

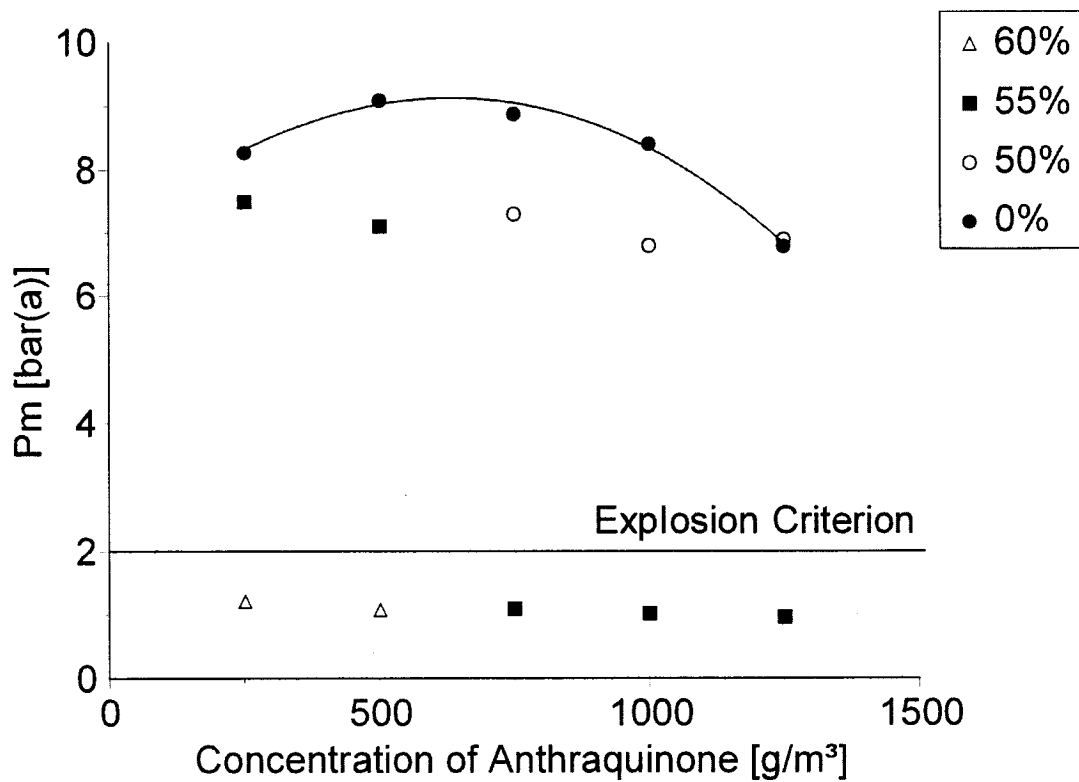


Figure 2.7: Explosion overpressure plotted against anthraquinone concentration for different amounts of monoammonium phosphate in mixture.

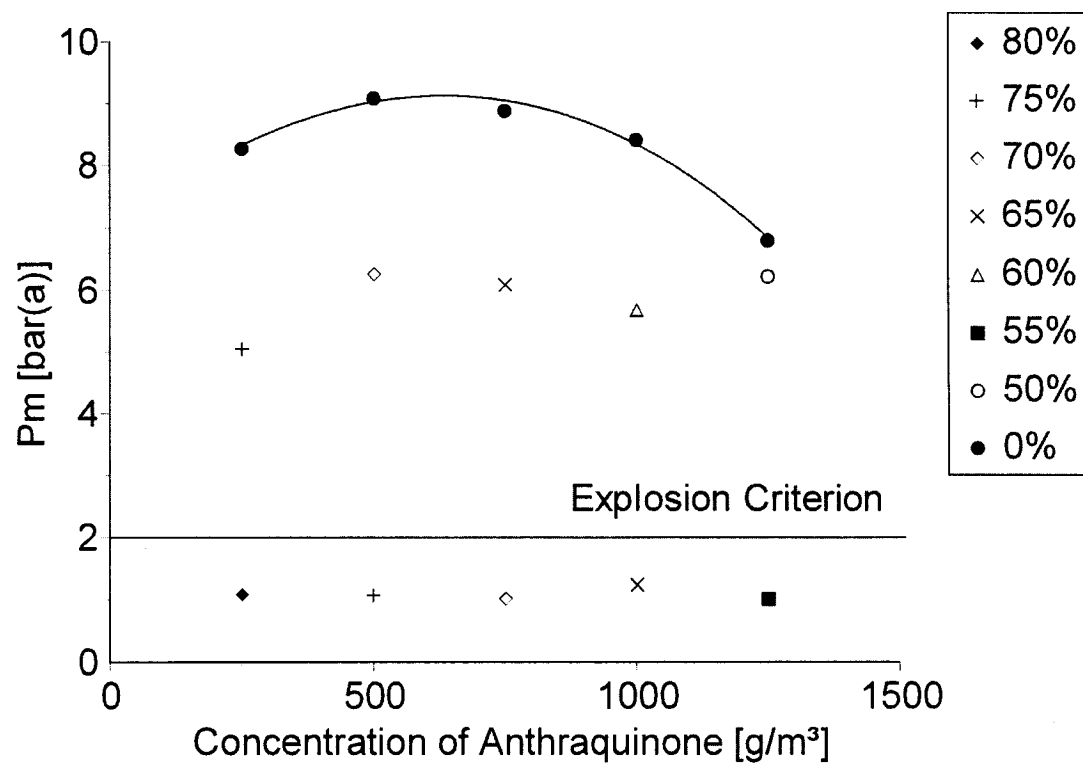


Figure 2.8: Explosion overpressure plotted against anthraquinone concentration for different amounts of sodium bicarbonate in mixture.

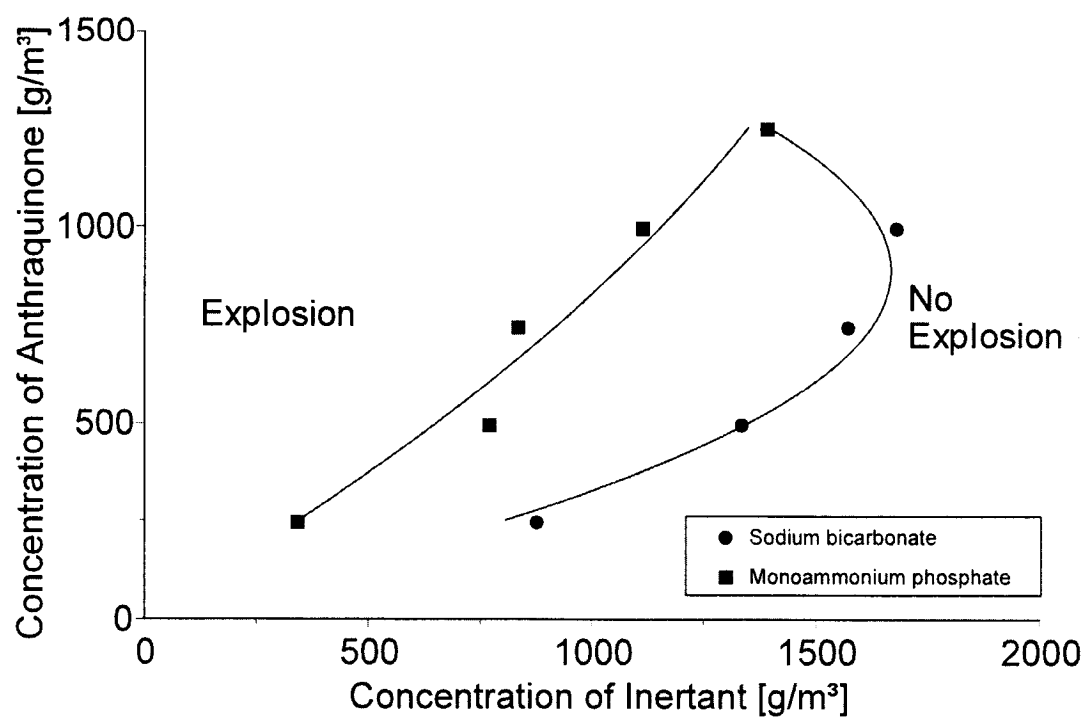


Figure 2.9: Comparison of monoammonium phosphate and sodium bicarbonate inerting curves for anthraquinone dust.

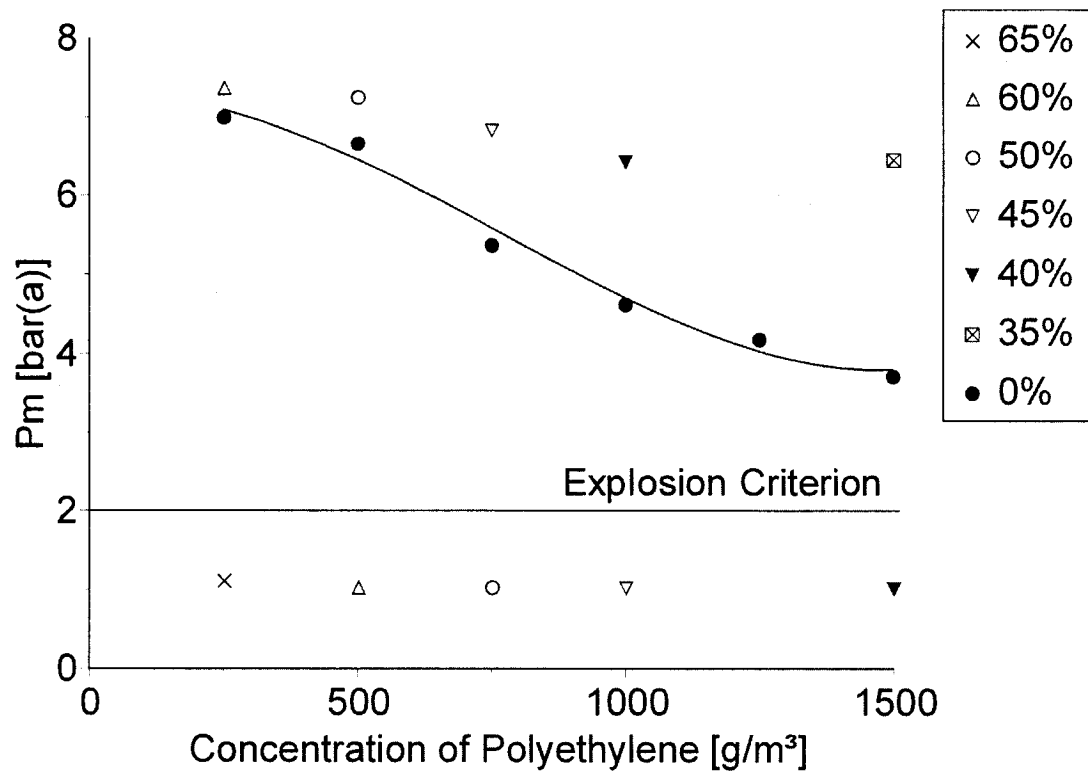


Figure 2.10: Explosion overpressure plotted against polyethylene concentration for different amounts of monoammonium phosphate in mixture.

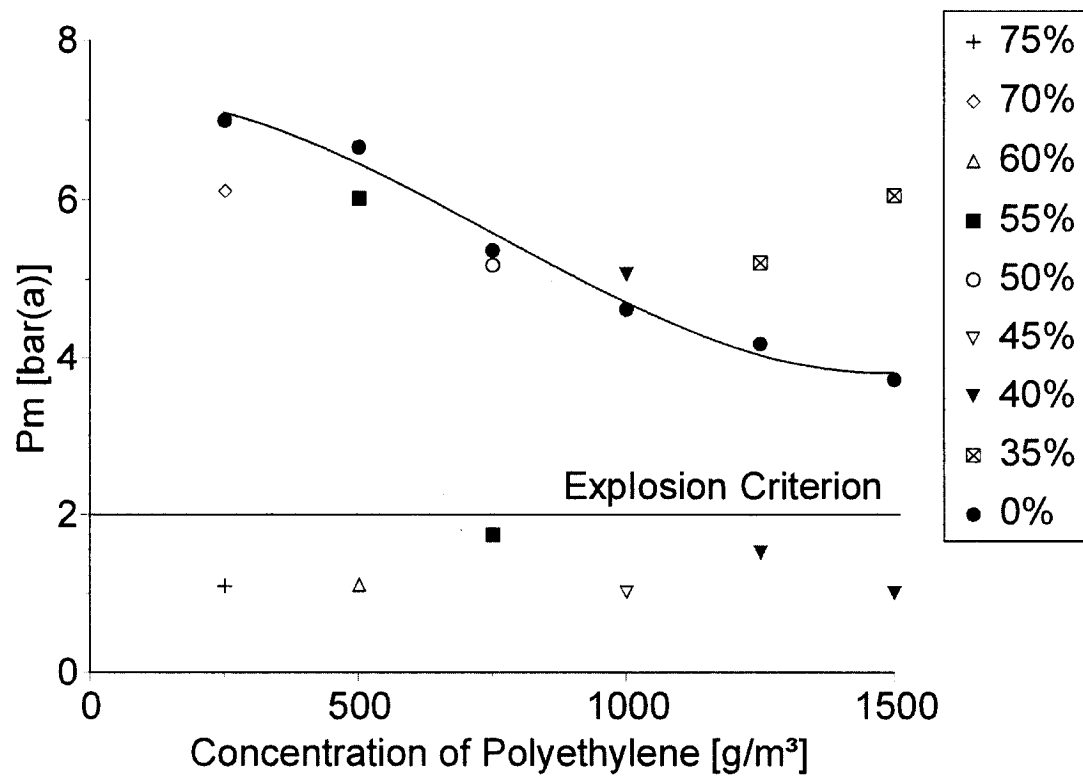


Figure 2.11: Explosion overpressure plotted against polyethylene concentration for different amounts of sodium bicarbonate in mixture.

In Figures 2.10 and 2.11, the trend observed previously, is repeated. For monoammonium phosphate, 60 to 65 % inertant is required to prevent an explosion at 250 g/m³; this relative amount decreases to between 35 and 40% at 1500 g/m³. The percent inertant may decrease if fuel concentration is increased further. With sodium bicarbonate as the inertant, the explosion was prevented with an inertant concentration between 70 and 75 % for low fuel concentrations. This suppression level steadily drops to between 35 and 40% at 1500 g/m³, showing a significant dependence of the inerting level on fuel concentration.

The figures also demonstrate the SEEP phenomenon. The behavior is very similar to that observed for aluminum inerting. When insufficient inertant to prevent an explosion is used, the resulting overpressure is greater than that observed for the pure fuel dust. For polyethylene, this occurred at all concentrations tested when using monoammonium phosphate as an inertant. However, when sodium bicarbonate was used as a suppressant, the SEEP phenomenon was only observed at the higher concentrations (> 1000 g/m³). The high rate of combustion of polyethylene may lead to the decomposition of the inertant.

In Figure 2.12, the concentration of fuel is plotted against the concentration of inertant in a similar manner as the aluminum results. It can be seen that inerting polyethylene with either monoammonium phosphate or sodium bicarbonate does not result in an MIC within the range of fuel concentrations tested. Inerting results with sodium bicarbonate show a slight curvature, thus hinting at the possibility of an MIC forming. The data show that monoammonium phosphate required less material to inert an explosion than sodium bicarbonate at low fuel concentrations, but at higher concentrations the inerting levels became similar.

All the results from the inerting experiments show a similar relationship. There is a definite relationship between the relative amount of inertant required to prevent an explosion and the fuel concentration. In all cases the relative amount of inertant decreased as fuel concentration increased. However, when the quantity of inertant is expressed in absolute terms in an inerting envelope, this trend becomes harder to see.

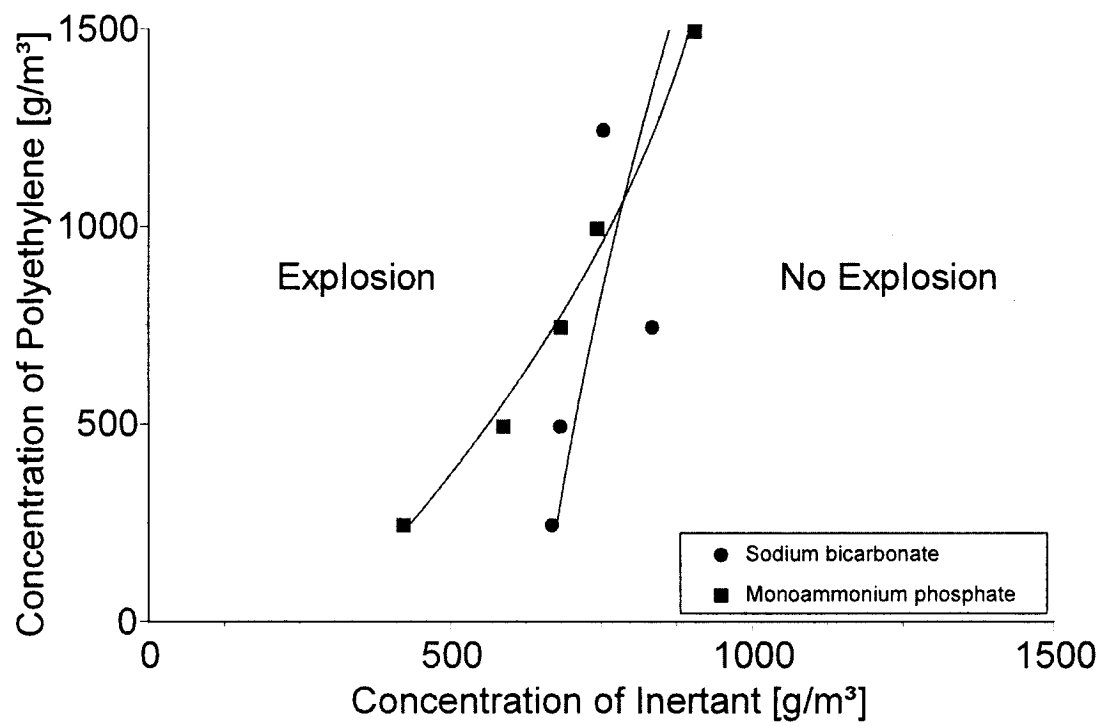


Figure 2.12: Comparison of monoammonium phosphate and sodium bicarbonate inerting curves for polyethylene dust.

In the case of inerting anthraquinone with sodium bicarbonate, there does appear to be a definite MIC at around 1700 g/m³ of inertant. In all the other cases there is no clear MIC in the concentration ranges tested. The other inerting envelopes may sweep out and form an MIC outside the range tested.

It could be argued that even though an MIC was not detected, the data do show the amount of inertant required to prevent an explosion for a broad fuel concentration range. This in itself is useful because it provides an indication of the amount of inertant that would be required to prevent an explosion if a reasonable quantity of dust were suspended. For example, if in a particular process situation it has been determined that a process upset would not produce an aluminum dust concentration greater than 2500 g/m³, then a suppression scheme can be devised so that the appropriate amount of inert matter will be used as a suppressant. The results from the current work show that an inertant concentration greater than 3000 g/m³ of monoammonium phosphate or sodium bicarbonate will prevent an explosion. This large amount of inertant will also prevent explosions at lower concentrations of aluminum. This information can then be used to design an explosion suppression scheme for any aluminum processing equipment so that the concentration of inertant (monoammonium phosphate or sodium bicarbonate) is greater than 3000 g/m³.

For safety reasons, it may be prudent not to use monoammonium phosphate to inert aluminum dust explosions. If insufficient quantities of this inertant are used, not only will it allow the explosion to proceed, but the heat from combustion will decompose the monoammonium phosphate producing combustible ammonia and hydrogen gas. It should be noted that several aluminum experiments that were insufficiently inerted in the current work produced large jet flames from the exhaust of the test vessel.

Another interesting result was the varying effectiveness of the two suppressants. Previous work at Fike has shown that monoammonium phosphate is a "better" inertant than sodium bicarbonate because less monoammonium phosphate is required to inert than sodium bicarbonate (for Pittsburgh pulverized coal and cornstarch, as shown in Figures 2.1 and 2.2). This agrees with results from Hertzberg *et al.* (1984) and Amrogowicz and

Kordylewski (1991), both of whom have shown that for premixed inerting experiments in small chambers (~20 L), monoammonium phosphate is more effective than sodium bicarbonate. However, Amrogowicz and Kordylewski (1991) argued that in suppression testing, sodium bicarbonate performed better than ammonium phosphate. The authors argued that the discrepancy was the result of the different abilities of monoammonium phosphate and sodium bicarbonate to devolatilize, as well as the different chemical kinetics of ignition and flame propagation. It is possible that monoammonium phosphate is better at preventing an ignition kernel from forming and starting a combustion wave propagating through the unburned dust. Sodium bicarbonate's effectiveness may be due to its ability to form chain terminating radicals in the combustion zone.

The experimental results from this work show that the organic fuels are inerted more effectively with sodium bicarbonate than monoammonium phosphate. Aluminum, the only metal tested, showed results where sodium bicarbonate performed marginally better as an inertant. This may be due to the nature of combustion. Aluminum dust combustion produces a very violent explosion. It has a much higher maximum overpressure and rate of pressure rise than all of the other dusts tested. In the case of coal, cornstarch, polyethylene and anthraquinone, the explosions were not as violent, with lower overpressures and rates of pressure rise observed. This in turn means that these organic dusts have relatively colder flames and slower rates of combustion. The ability of monoammonium phosphate to absorb and dissipate heat may favor these lower rates of combustion. The violence of the aluminum dust explosion may overwhelm monoammonium phosphate's ability to absorb heat quickly enough to be as effective.

Higher rates of combustion of the fuel dust may lead to the decomposition of the inertant. This can be seen in the aluminum and polyethylene explosion. These were so violent that they lead to the decomposition of a significant quantity of inertant (in explosible mixtures of fuel and inertant). This created overpressures that were greater than the overpressures observed for the fuel dust alone.

It is also apparent from the experimental data presented here and previous work done at Fike that simple organic molecules such as cornstarch, polyethylene and anthraquinone

do not form distinct inerting envelopes in the fuel concentration range tested. As a result they do not show a distinct MIC (except for cornstarch and anthraquinone inerting with sodium bicarbonate), while a complex organic fuel, such as coal dust does form a distinct inerting envelope. The “nose” indicating the MIC is easily seen. Sodium bicarbonate may be more effective than monoammonium phosphate at absorbing heat from the explosion quickly enough to prevent propagation, resulting in an MIC for anthraquinone and cornstarch.

The energy delivery rate from the combustion of simple organic compounds may be too fast for the inertant to absorb sufficient energy quickly enough to prevent combustion. This, in conjunction with the fact that these simple organic molecules have lower energy requirements to start combustion (low minimum ignition energy levels), may lead to a broad sweeping inerting envelope from which the MIC cannot easily be detected. Experiments at higher concentrations are hindered by physical limitations of the test vessel.

2.6 CONCLUSIONS

Inerting envelopes were produced for aluminum, anthraquinone and polyethylene using monoammonium phosphate and sodium bicarbonate as inertants.

The relationship between the relative amount of inertant required to prevent an explosion and the fuel concentration has been shown. In all cases the relative amount of inertant decreased as fuel concentration increased. However, when the quantity of inertant is expressed in absolute terms in an inerting envelope, this trend becomes harder to see. For some of the fuel and inertant mixtures tested, there were no definitive MIC's.

Previous work at Fike, and work by Hertzberg *et al.* (1984) and Amrogowicz and Kordylewski (1991), have shown that for premixed inerting experiments monoammonium phosphate is a more effective suppressant than sodium bicarbonate. The experimental results from this work in a 1-m³ vessel agree with their findings that the organic fuels require less monoammonium phosphate to inert an explosion than sodium bicarbonate at low fuel concentrations. At higher fuel concentrations sodium bicarbonate

became more effective than monoammonium phosphate for simple organic compounds, such as polyethylene and anthraquinone. This is similar to the inerting envelope of cornstarch in Figure 2.2. It appears that for coal, a more complex organic fuel, monoammonium phosphate remains a more effective suppressant at high fuel concentrations. Aluminum was inerted marginally better by sodium bicarbonate. This may be due to the nature of combustion. Monoammonium phosphate may be a more effective suppressant suited to inert slower, low temperature burning of organic fuels while sodium bicarbonate may be suited for faster, hotter metal combustion.

The combustion of aluminum, as well as polyethylene, was violent enough to lead to the decomposition of a significant quantity of inertant, leading to explosion parameters that were higher than those observed for the pure dust. This phenomenon has been termed Suppressant Enhanced Explosion Parameter by Fike and given the acronym SEEP. This may pose a challenge when designing an explosion suppression scheme since the use of insufficient quantities of suppressant may increase the hazard from the explosion.

Simple organic molecules such as polyethylene and anthraquinone do not form distinct inerting envelopes in the fuel concentration range tested. As a result, they do not form an MIC (except for anthraquinone inerting with sodium bicarbonate). The inerting envelope may only exist for complex organic compounds. The energy delivery rate from the combustion of simple organic compounds may be too fast for the inertant to absorb sufficient energy quickly enough to prevent combustion. This, in conjunction with low minimum ignition energy levels, may lead to a broad sweeping inerting envelope from which the MIC cannot be detected in the concentration ranges tested. The alternative is to use a worst case scenario approach and use the highest absolute concentration of inertant required to prevent an explosion for the highest fuel range tested. This could lead to an effective MIC.

The new flammability limit parameter MIC described here has the potential of being an important tool in the design of explosion suppression systems. However, some fuel and inertant mixtures did not show an MIC in the concentration ranges tested. In these cases an effective MIC can be used. The effective MIC can be estimated by determining the

maximum amount of fuel that can be suspended in air due to a process upset and finding the amount of inertant required to prevent an explosion for this concentration. Fuel concentrations below this maximum amount will also be inerted. The effective MIC can then be used as an estimate of the quantity of suppressant required to prevent an explosion.

2.7 FUTURE WORK

A key parameter in inerting and suppression testing is the vessel volume. Research has shown the vessel volume to be important because too small a vessel will not allow for proper flame front development and may underestimate the inerting requirement. A related parameter is the ignition energy. An ignition source that is too large may lead to overdriving the explosion and overestimating the inertant requirement.

The importance of the MIC has been stressed in the current paper. It is important to perform MIC testing on combustible dusts for proper protection of process equipment. To do this may require a considerable number of tests; therefore it may be beneficial to perform tests in a smaller chamber. It would be necessary to determine if wall quenching and overdriving have a significant effect on the inerting envelope in the smaller explosion chamber. To evaluate the effectiveness of smaller chambers for inerting level determination, inerting tests will be performed in the DalTech 20-L Siwek chamber using aluminum, anthraquinone, polyethylene, Pittsburgh pulverized coal and cornstarch as fuels and monoammonium phosphate and sodium bicarbonate as inertants.

2.8 ACKNOWLEDGEMENT

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3 DUST EXPLOSION INERTING IN A SMALL-SCALE 20-L SPHERICAL CHAMBER

This section was originally published as:

A. Dastidar and P. Amyotte, "*Determination of minimum inerting concentrations for combustible dusts in a laboratory-scale chamber*", **Trans IChemE, Process Safety and Environmental Protection**, vol. 80, Part B, pp. 287-297, 2002*. The text and figures in this section are identical to that of the published paper with the exception that section numbers have been added, and figure and table numbers have been changed, to reflect the thesis format.

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3.1 ABSTRACT

Experiments were performed to compare intermediate-scale (1-m^3) and laboratory-scale (20-L) inerting results. In general, laboratory-scale inerting levels were higher than intermediate-scale values. This can be attributed to the use of a strong ignition source to initiate the test, which may have overdriven the explosions in the smaller test vessel. Previously reported agreement between the smaller test vessel and full-scale experiments may be due to overdriving in the 20-L chamber, leading to high inerting levels similar to those encountered in full-scale tests due to flame acceleration. Use of weaker ignition sources in the laboratory-scale chamber did produce inerting levels similar to those observed in the intermediate-scale vessel.

A new flammability limit parameter has been defined as the Minimum Inerting Concentration (MIC; in units of mass concentration, i.e. g/m^3). This is the concentration of inertant required to prevent a dust explosion regardless of fuel concentration. Previous experimental work in a 1-m^3 spherical chamber has shown this flammability limit to exist for some fuels. In the current work, inerting experiments were performed in a 20-L Siwek chamber using identical materials to those used in the 1-m^3 chamber. The results show that an MIC can be determined in the smaller test chamber; however, there is a strong dependence on ignition energy strength used to initiate the explosion.

In the 20-L tests, as in the 1-m^3 tests, not all combustible dust and inertant mixtures showed a definitive MIC, although they did show a strong dependence between inerting level and suspended fuel concentration. As the fuel concentration increased, the amount of inertant required to prevent an explosion decreased. Even though a definitive MIC was not found for all of the dusts, an effective MIC can be estimated from the data. The use of MIC data can aid in the design of explosion suppression schemes.

3.2 INTRODUCTION

Dust explosions are a serious hazard in the process industries and suppressants are widely used to provide protection against such explosions. For suppression to be effective, it is important to determine the amount of inertant required to prevent an explosion of the dust at any concentration. Inerting concentrations can be determined by performing suppression tests with laboratory-scale equipment or with large- or full-scale equipment. Laboratory-scale tests are often done due to the cost and effort required for full-scale testing.

An additional flammability limit parameter can be defined for inerting dust clouds with particulate material. This new parameter is called the Minimum Inerting Concentration (MIC; in units of mass concentration, i.e. g/m^3). The minimum inerting concentration is the lowest inert dust concentration at which a dust explosion is not possible for any fuel concentration. MIC values can be determined by measuring the full flammability curve for the fuel-air-inert dust mixture. This approach differs from suppression testing in that the fuel and inertant are pre-mixed and collectively injected into the test vessel.

The use of the MIC is an important component in the design of explosion suppression systems for industrial equipment and chemical isolation barriers in pipes. Suppression and isolation designs having inert agent concentrations below the MIC will have the possibility of allowing dust explosions to occur. Therefore, the MIC provides guidance for the safe design of suppression and chemical barrier systems.

Previous experiments (Dastidar *et al.* (1998c), Dastidar *et al.* (1999)) conducted with the Fike 1-m³ spherical chamber (Blue Springs, MO) used five different combustible dusts: aluminum, anthraquinone, polyethylene, Pittsburgh pulverized coal and cornstarch. The inertants used were limestone, monoammonium phosphate and sodium bicarbonate, all of which have been shown to be effective explosion suppressants. Because it is economically advantageous to perform MIC tests in smaller explosion vessels, these same dusts (fuel and inertant) were tested in the current work in a 20-L Siwek chamber. The primary consideration was to study the influence of test vessel volume on the MIC. Too small a vessel will not allow for proper flame front development and may

underestimate the inerting requirement. A related parameter that was investigated is the applied ignition energy. An ignition source that is too large may lead to overdriving the explosion, thus overestimating the inerting requirement.

3.3 BACKGROUND

Figure 3.1, from Moore and Siwek (1992), is a pictorial representation of suppressant requirements to mitigate an explosion coupled with suppressant delivery from high-rate discharge canisters. The quantity of suppressant required to mitigate an explosion begins at some initial value at zero time, and increases rapidly as the explosion fireball increases in size. This initial amount of suppressant is dependent upon material properties and the nature of the ignition source. The upward curvature of the line is dependent upon the nature of flame propagation of the material in a given vessel geometry.

The delivery of the suppressant from the discharge canisters begins after an initial delay, which is dependent upon the explosion detection system. The curve then increases rapidly and begins to level off as the suppressant propellant is spent. For adequate suppression of an explosion, the suppressant delivery curve must cross and exceed the suppressant requirement curve. The nature and curvature of the suppressant delivery curve is dependent upon the design characteristics of the suppressant device (e.g. number and type of detectors, number and size of discharge canisters, and flow rate from the discharge canisters).

A key factor in determining if the two curves cross is the intersection of the curve showing the quantity of suppressant required to mitigate an explosion, with the ordinate (i.e. the suppressant requirement at zero time). This value is the inerting level, or the suppressant requirement when the suppressant and the fuel are intimately mixed. In a dust explosion situation the quantity of fuel present in the operating unit may not be known; therefore it would be beneficial to know the suppressant requirements at zero time

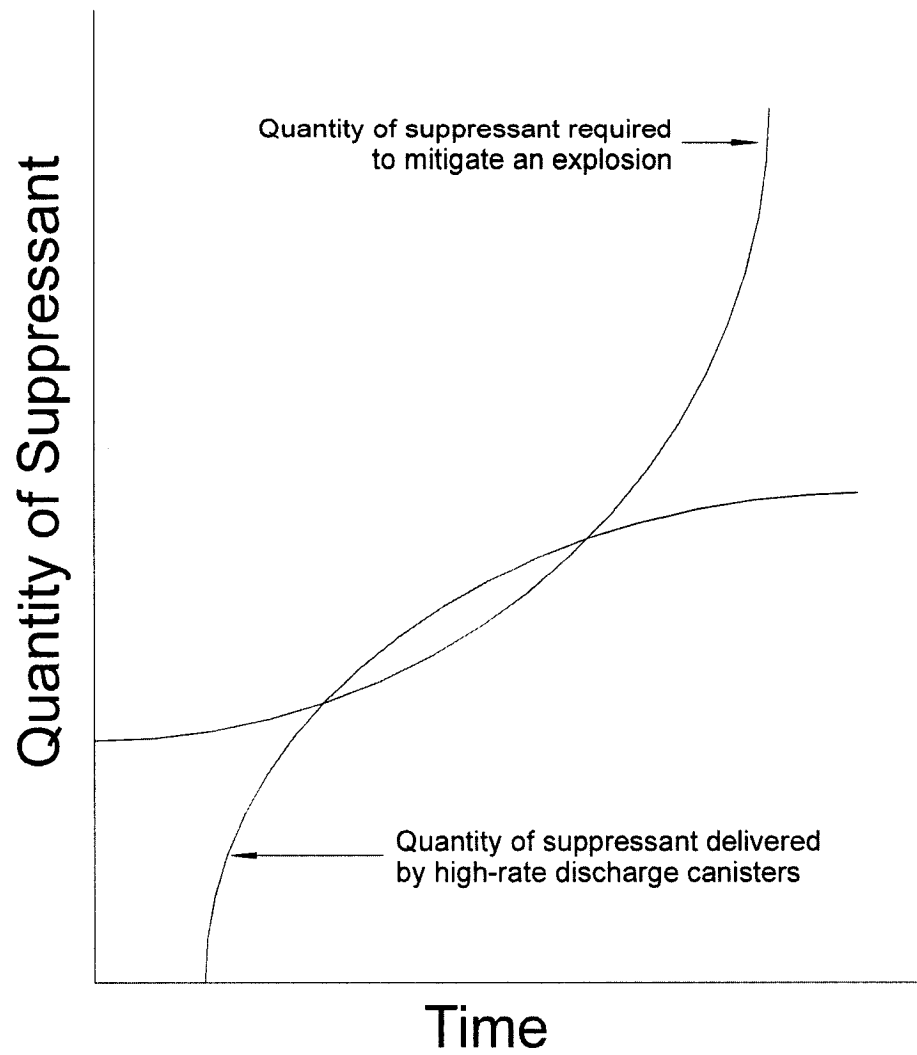


Figure 3.1: Suppressant requirement and delivery curve (Moore and Siwek, (1992)).

regardless of fuel concentration. This is provided by the MIC. Being able to experimentally obtain MIC's similar to those found in the 1-m³ inerting work (Dastidar *et al.* (1999), Dastidar *et al.* (1998c)) in a smaller chamber (e.g. 20-L Siwek chamber), would greatly assist in reducing the cost accrued in explosion suppression design.

Previous work by Dastidar *et al.* (1997) has shown that there is a strong interdependence of the relative amount of premixed inertant required to prevent an explosion, and the fuel concentration. The authors report from tests of Pittsburgh and Pocahontas pulverized coals that fuel concentrations near stoichiometric volatile-air mixtures required more limestone to prevent an explosion than higher fuel concentrations. These stoichiometric volatile-air mixtures represent the fuel concentration that produces the maximum explosion overpressure. At volatile-air ratios in excess of stoichiometric there is insufficient oxygen for complete combustion, and the unreacted material acts as a thermal sink, helping to inert the explosion. As a result, a decrease in overpressure is observed. For inerting work this implies that at high fuel concentrations the excess fuel dust acts to increase the effective thermal sink in the dust mixture. Since the fuel aids the inertant, there is less inertant needed to prevent an explosion.

The same point was argued by Mintz (1993); by increasing the concentration of fuel in a fixed volume chamber, a dense dust cloud is formed. In such a cloud, when a fuel particle burns, all the oxygen in its immediate vicinity is consumed in the reaction zone. This, however, will also consume the oxygen that would be required by the neighboring fuel particle for combustion. The transient nature of the combustion propagation wave also means that there is insufficient time for oxygen to be transported to the particle in a dense dust cloud. This implies that even though there may be sufficient oxygen for combustion globally, there is not enough oxygen in the local vicinity. As a result, the neighboring particle does not burn. This unburned particle then acts as a heat sink reducing the flame temperature and the explosion overpressure. By adding an inertant to the dust mixture, a dense dust cloud is formed at low fuel concentrations thereby hindering the transport of oxygen to the fuel particle in time for combustion to occur, as well as acting as a thermal sink.

Inerting experiments (1-m^3) at Fike (Dastidar *et al.* (1999), Dastidar *et al.* (1998c)) have shown a similar concentration dependence of explosion inerting. By plotting the data as fuel and inertant concentrations, the results form an inerting envelope similar to a traditional flammability envelope. Figure 3.2 shows the inerting envelope for Pittsburgh pulverized coal (Dastidar *et al.* (1999), Dastidar *et al.* (1998c)). The data points represent the explosibility limit of the fuel-inertant mixture. They are interpolated by averaging the highest inertant concentration tested that produced an explosion with the lowest inertant concentration tested that did not produce an explosion for a given fuel concentration. The area to the left of the curve represents the explosible area. In this area, there is insufficient inertant to prevent an explosion. The area to the right of the curve represents the nonexplosible area; here there is sufficient inertant to prevent an explosion. The “nose” of the envelope represents the least amount of inertant that would prevent an explosion regardless of fuel concentration. This point is the MIC, the least amount of inertant required to mitigate an explosion, when mixed intimately with the fuel. It is also the concentration of inertant (independent of fuel quantity) at which, from Figure 3.1, the suppressant-required curve intersects the ordinate of the graph in the ideal situation where flame propagation is independent of ignition strength. In practice, however, it should be noted that factors such as initiation point location(s) and ignition energy density may contribute to this intersection point. Thus, the intersection point on Figure 3.1 may be greater than the MIC.

The data trend shown in Figure 3.2 provides a useful platform from which adequate protection measures can be implemented. Since it is difficult to determine at any given time the actual suspended dust concentration in process equipment, or even the potential suspended dust concentration from a process upset, estimates are made in designing explosion protection equipment. One of these estimates is to take the worst-case scenario and perform inerting experiments at the fuel concentration that produces the highest overpressure. This results in a relative amount of inertant required to prevent an explosion. The inerting level so determined cannot be used as an absolute concentration of inertant because higher fuel concentrations would require greater amounts of inert material to prevent an explosion (even though the relative concentration may be less). If

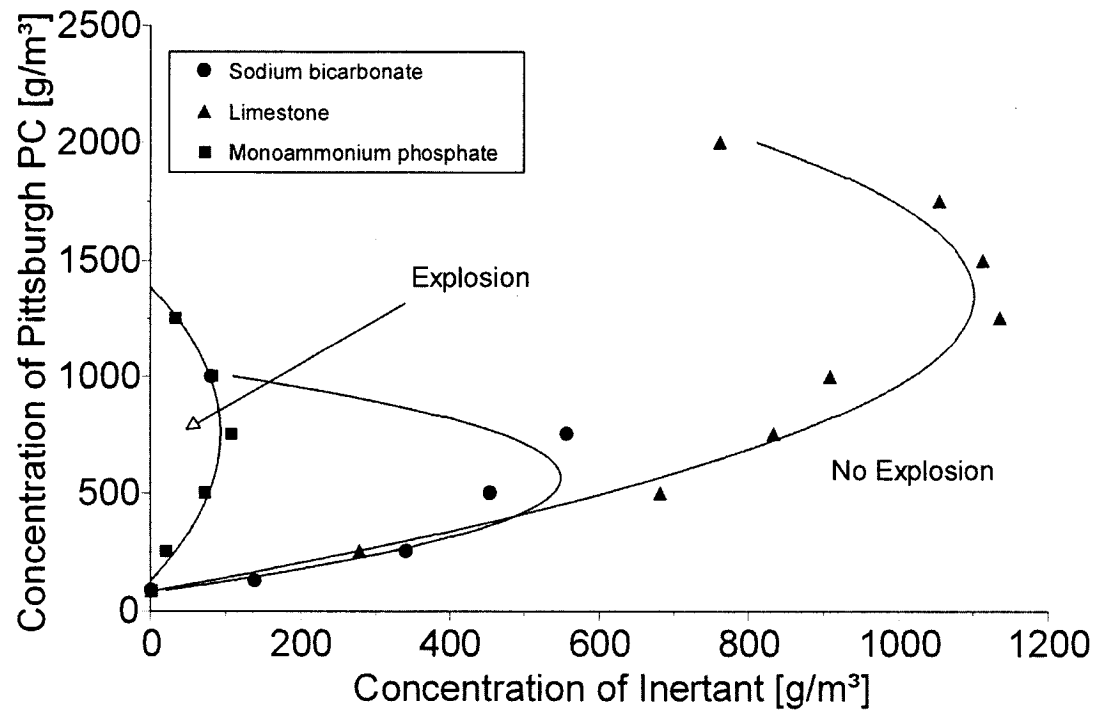


Figure 3.2: Inerting envelope for Pittsburgh pulverized coal dust with sodium bicarbonate, monoammonium phosphate and limestone as inertants. Experiments conducted in a spherical 1-m³ chamber using two 5-kJ ignitors as ignition source.

the inerting level was to be maintained as a constant ratio, large quantities of inertant would be required at high fuel concentrations. While this may guarantee safety, it poses certain equipment design problems. Suppression devices have to be very large and complicated to be able to introduce such large quantities into the process unit, and the process units themselves have to be designed to accommodate these larger suppression devices.

If, however, an MIC were to exist for a dust, suppression strategies could be designed to introduce a fixed concentration of inertant. A fixed number of high-rate discharge containers could be attached to a process unit to deliver this fixed concentration of inertant. At both low and high fuel concentrations there would be enough inertant to prevent an explosion. Thus, if the concentration of explosible dust were to increase or decrease in the unit, there would always be sufficient inertant to suppress an explosion.

A key point which must be made is that the MIC is an ignition limit, not a suppression limit. This is due to the fact that the inert matter is premixed with the fuel when injected into the test vessel. This intimate contact between the fuel and inertant represents an ideal case. For suppression there may be losses in inertant effectiveness due to the type of dispersion from the discharge canister and incomplete mixing between the inertant and the fuel.

3.4 EXPERIMENTAL

Experiments were performed in a 20-L Siwek chamber (Siwek (1980), Siwek (1977)). A schematic diagram of the chamber and auxiliary equipment is shown in Figure 3.3. The spherical test chamber has a volume of 20 L and is made of stainless steel with a maximum allowable working pressure of 20 bar(g). The vessel is surrounded by a water jacket which is used to control the initial temperature of the test chamber. The top access cover is fitted with ignition leads. Chemical ignitors, similar to those used in the 1-m³ chamber, are connected to the ignition leads. The ignitors are manufactured by Sobbe (Germany) and are composed of 40% zirconium, 30% barium nitrate and 30% barium

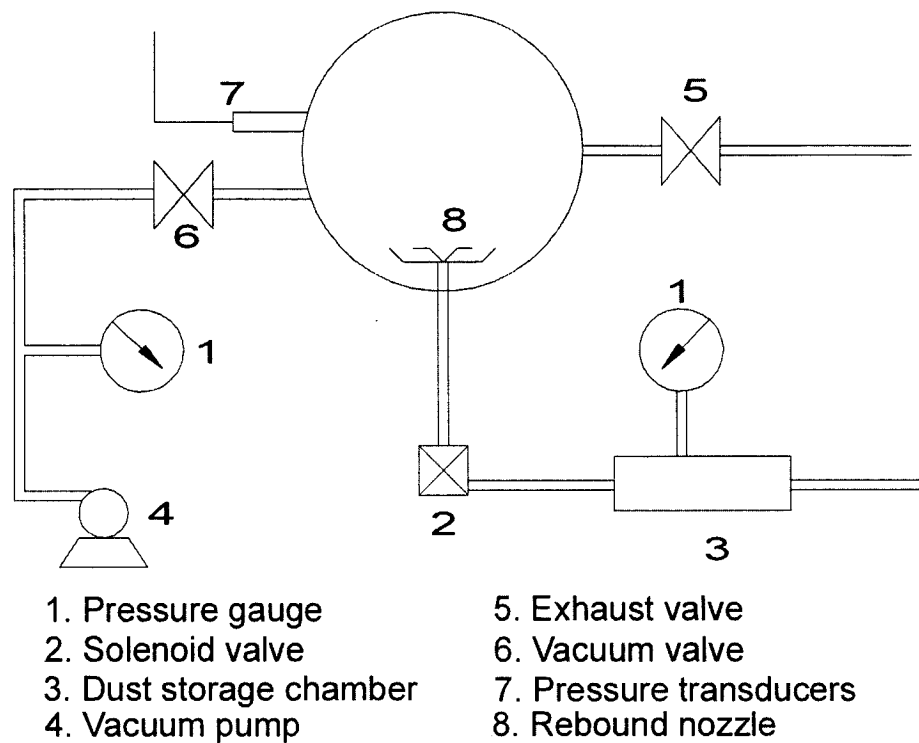


Figure 3.3: 20-L Siwek chamber.

peroxide. An ignitor with a stored energy of 5 kJ has 1.2 g of this mixture and releases its energy in about 10 ms.

The desired amounts of fuel dust and inert dust for a given experiment are mixed and placed in the dust storage chamber (volume of 0.6 L). The ignitors are attached to the ignition leads and the test chamber is sealed and partially evacuated to 0.4 bar(a). The computer control program is then initiated and the dust storage chamber pressurized to 20 bar(g) with extra dry compressed air. The computer then opens the solenoid valve between the dust storage chamber and the test chamber, dispersing the air and dust mixture into the test chamber through a Kühner rebound nozzle and raising the chamber pressure from 0.4 bar(a) to 1 bar(a).

The computer then energizes the ignition source after a time delay of 60 ms. The computer records the pressure-time history of the explosion using two piezoelectric transducers installed flush with the interior of the chamber. The pressure-time trace provides the maximum overpressure (P_{ex}), the maximum overpressure due to the explosion of the dust mixture (P_m) using a correction algorithm to compensate for the pressure increase from the ignitor as well as vessel cooling, and the maximum rate of pressure rise ($((dP/dt)_m)$) for a given test. A P_m value of 1 bar(g) (2 bar (a)) was used as the explosion criterion to delineate a non-explosion from an explosion. This is the same criterion as used in our previous work (1-m³ and 20-L) (Dastidar *et al.* (1997), Dastidar *et al.* (1998c) and Dastidar *et al.* (1999)).

As previously mentioned, the dusts used were aluminum, anthraquinone, cornstarch, Pittsburgh pulverized coal and polyethylene as fuels, and monoammonium phosphate, sodium bicarbonate and limestone (for cornstarch and Pittsburgh pulverized coal dust) as inertants. The choice of fuels was made to represent materials commonly used in the process industries: a metal dust, a chemical intermediate for an organic dye, a food product, fuel used in energy production and a typical polymer. The inertants, monoammonium phosphate and sodium bicarbonate, are commonly used suppressants in the explosion protection field. Limestone is commonly used in mines to prevent coal dust explosions. The experimental test matrix is given in Table 3.1.

Table 3.1: Test matrix for experiments conducted in the 20-L Siwek chamber.

Dust	Concentration Range [g/m ³]	Inertant	Ignition Energy [kJ]
Aluminum	250 – 1000	Monoammonium Phosphate	5
		Sodium Bicarbonate	5
Anthraquinone	250 – 1000	Monoammonium Phosphate	5
		Sodium Bicarbonate	5, 1
Cornstarch	250 – 1250	Monoammonium Phosphate	5
		Sodium Bicarbonate	5, 1
		Limestone	5
Pittsburgh Pulverized Coal	250 – 1500	Monoammonium Phosphate	5, 2.5, 1, 0.5
		Sodium Bicarbonate	5, 1
		Limestone	5
Polyethylene	250 – 1250	Monoammonium Phosphate	5
		Sodium Bicarbonate	5

Particle size measurements of all dusts were made using a Malvern Instruments 2600 Series analyzer based on the principle of laser diffraction. The results of the particle size analyses are given in Table 3.2 in which the arithmetic volume or mass mean diameter, D_w , is shown.

The explosion parameters (overpressure and rate of pressure rise) of the pure fuel dusts were determined as a function of concentration. This was achieved by varying the amount of dust placed in the discharge chamber. The effect of inertant was then determined for each fuel concentration by measuring the explosion parameters as inertant was added to the mixture. Data treatment was carried out as described by the following example.

Table 3.2: Particle sizes of fuel and inertant dusts used for MIC testing.

Dust	< 100 μm [wt %]	< 25 μm [wt %]	Volume Mean Diameter D_v [μm]
Aluminum	90	50	17
Anthraquinone	92	32	46
Cornstarch	100	87	17
Pittsburgh Pulverized Coal	93	14	60
Polyethylene	83	17	64
Monoammonium Phosphate	83	18	62
Sodium Bicarbonate	97	32	37
Limestone	94	49	41

Figure 3.4 is a graph of the explosion data previously determined for Pittsburgh pulverized coal dust in the Fike 1-m³ chamber using sodium bicarbonate as an inertant. The open circles represent experiments where the combustion overpressure of a given fuel and inertant mixture did not meet, or exceed, the 1 bar(g) explosion criterion. The closed circles represent fuel and inertant mixtures where the criterion was met. The inerting level was interpolated by averaging the highest inertant concentration tested that produced an explosion with the lowest inertant concentration tested that did not produce an explosion for a given fuel concentration. In this manner, the sodium bicarbonate inerting envelope given in Figure 3.2 was constructed. The 20-L data plots constructed in the current work (Figures 3.5 – 3.20) were prepared in a similar manner.

3.5 RESULTS AND DISCUSSION

3.5.1 Influence of Vessel Size

In this section we report on the comparison of inerting levels measured in the current work (20-L) and in our previous 1-m³ experiments (Dastidar *et al.* (1998c), Dastidar *et al.* (1999)). The initial inerting experiments in the 20-L chamber were performed with a 5-kJ ignition source. The selection of this ignition strength was based on our previous experimental work (Dastidar *et al.* (1997)). Results from this previous study (Dastidar *et al.* (1997)) showed good agreement between the mine-scale inerting of coal dust with

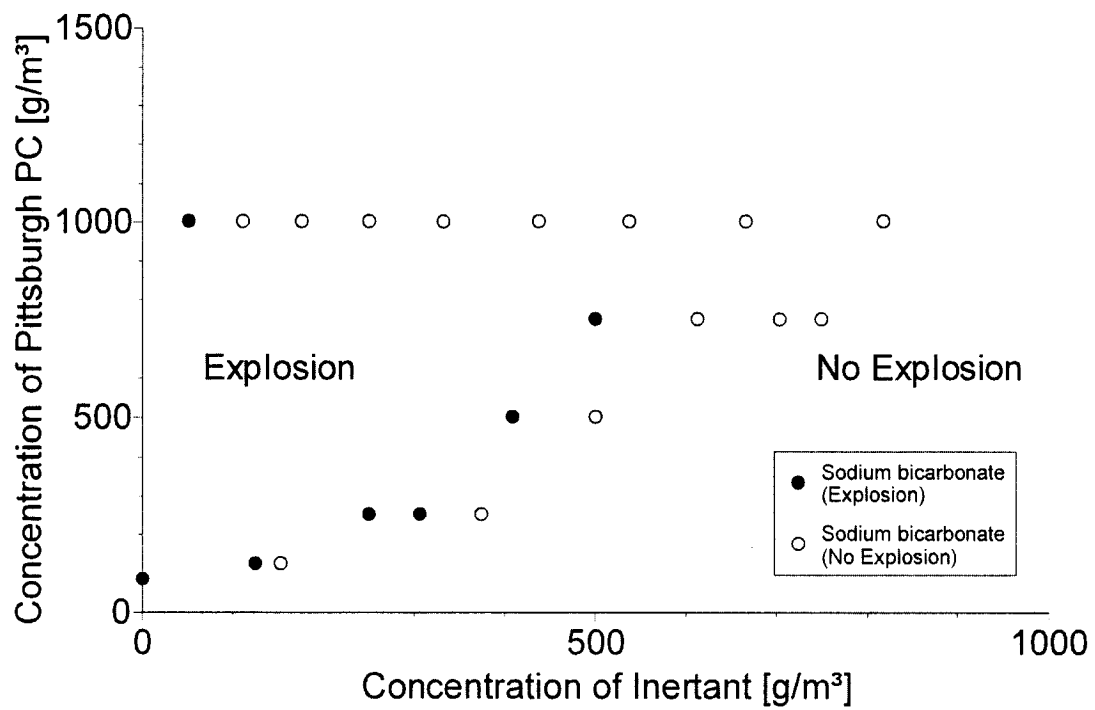


Figure 3.4: Development of inerting envelope using Pittsburgh pulverized coal as fuel and sodium bicarbonate as inertant (1-m³ chamber).

rock dust, and 20-L experiments, when a 5-kJ ignition source was used in the smaller chamber. The standard ignition strength used in the 1-m³ chamber is 10 kJ (ISO 6184/1 (1985), ISO 6184/4, (1985)). Thus, the data legends shown in Figures 3.5 – 3.16 indicate an ignition energy of 5 kJ for the 20-L plots and 10 kJ for the 1-m³ plots.

A difficulty often encountered in the field of explosion mitigation is the dearth of available experimental data in the open literature. These data are typically proprietary and their scarcity not only inhibits the design of explosion mitigation systems, but also the development of the science in this field. In an attempt to disseminate widely such data, we have provided comprehensive figures detailing all of the experimental results from the current work.

Figures 3.5 and 3.6 show the results of the inerting tests for aluminum using monoammonium phosphate and sodium bicarbonate, respectively, as inertants in the 20-L and 1-m³ chambers. For low aluminum dust concentrations (below 1000 g/m³), the inerting levels are in good agreement. For fuel concentrations of 1000 g/m³ and greater, the concentration of inertant required to prevent an explosion in the 20-L chamber, using a 5-kJ ignition source, is greater than that required in the 1-m³ chamber.

In the 1-m³ curves shown in Figures 3.5 and 3.6 there is a slight upward trend of the plotted lines; however, there is no observed minimum inerting concentration. The curvature is an indication that the higher aluminum concentrations require relatively less inertant to prevent an explosion than lower concentrations of aluminum. The influence of fuel concentration on inertant requirements for the mitigation of an explosion is different in the 20-L than in the 1-m³ chamber. In the 20-L vessel, low concentrations of aluminum required relatively less inertant to prevent an explosion than higher concentrations of aluminum. From Fig. 3.5 (20-L), for 250 g/m³ of aluminum, 50% inert material is required to prevent an explosion, and 60% inert material is required for 500 g/m³ of aluminum. The relative inerting level then remains constant at 65% for the remaining concentrations tested in the 20-L chamber. This is the opposite of the trend observed in the 1-m³ chamber, where the relative concentration of inert matter gradually decreases.

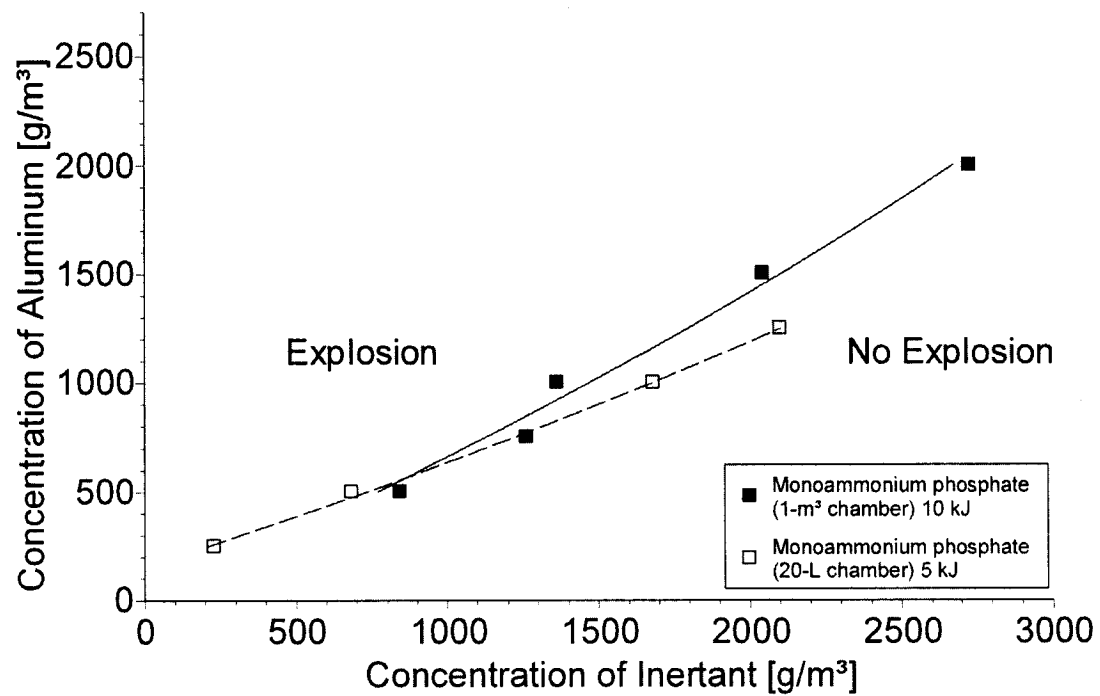


Figure 3.5: Comparison of 1-m³ and 20-L chamber inerting curves for aluminum using monoammonium phosphate as inertant.

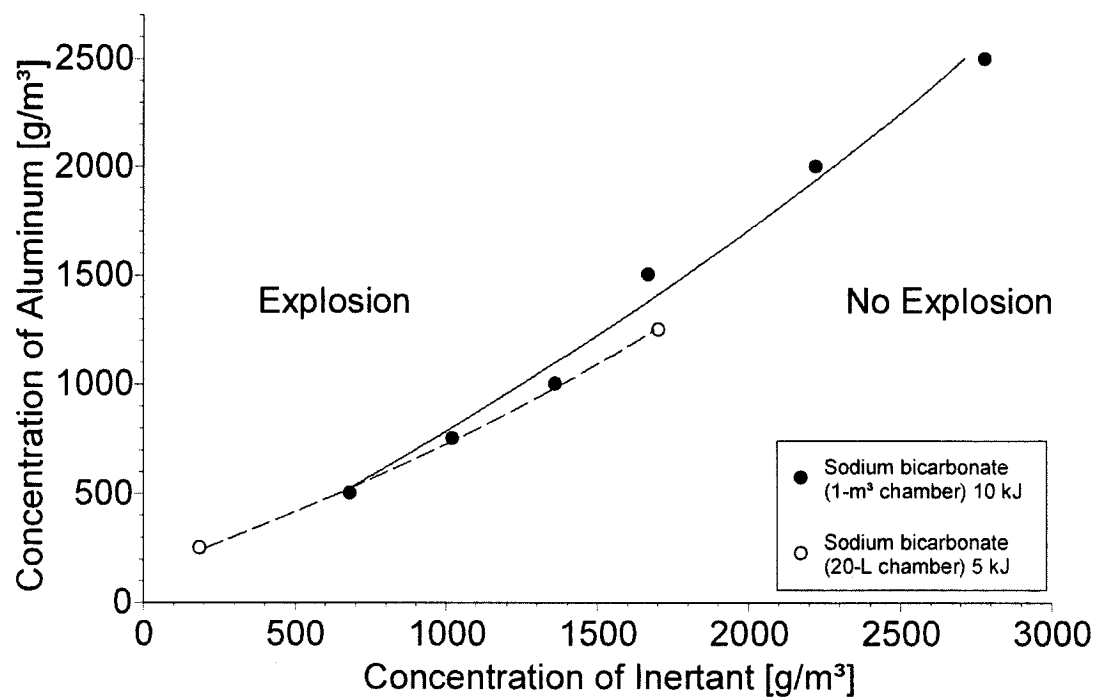


Figure 3.6: Comparison of 1-m³ and 20-L chamber inerting curves for aluminum using sodium bicarbonate as inertant.

This difference observed between the relative inerting levels in the 20-L chamber and the 1-m³ chamber may be attributed to lower explosion overpressures in the 20-L chamber for pure aluminum. The low explosion overpressures observed in the 20-L chamber at low fuel concentrations such as 250 g/m³ indicate an approaching minimum explosible concentration. Since test conditions are near the limit flame concentration, less inert material is required to mitigate the explosion in the 20-L volume than in the 1-m³ volume. Lower explosion overpressures in the 20-L chamber (than in the 1-m³ chamber) at higher fuel concentrations may be an indication of wall quenching. The reasoning behind the need for relatively less inertant to mitigate an explosion at higher fuel concentrations, above stoichiometric fuel/air concentrations, is that the excess unburned fuel in the oxygen-lean propagating flame front acts as an inerting agent. However, if the flame front is prematurely quenched (or partially quenched) by the wall, sufficient oxygen is present to facilitate combustion. Since the unburned fuel does not assist in the abstraction of heat from the reaction zone, the required level of additional inertant to mitigate combustion remains the same.

A phenomenon observed in the inerting of aluminum in the 1-m³ chamber was that if insufficient inertant is used in the fuel/inertant mixture, the explosion overpressure is enhanced to levels greater than that for the pure dust (Dastidar *et al.* (1999), Dastidar *et al.* (1998c)). This phenomenon has been termed SEEP (Suppressant Enhanced Explosion Parameter). It can be attributed to decomposition of the inertant by heat from the combustion of the aluminum. In the case of sodium bicarbonate, carbon dioxide is produced and for monoammonium phosphate, ammonia and hydrogen, both flammable gases, are produced. This raises a concern for the inerting of hot burning metal dusts. If insufficient suppressant is present, this could lead to greater dangers than if no suppressant were used. This phenomenon has also been observed in the current work involving 20-L chamber inerting tests, although the extent of enhancement of the explosion overpressure was not as great as in the 1-m³ chamber. In both cases (20-L and 1-m³) the phenomenon was more apparent in the aluminum/sodium bicarbonate system than with aluminum and monoammonium phosphate.

Figures 3.7 and 3.8 show the results of the inerting tests for anthraquinone using monoammonium phosphate and sodium bicarbonate, respectively, as inertants in the 20-L and 1-m³ chambers. In all cases, the inerting level in the 20-L chamber, using a 5-kJ ignition source, is much greater than that observed in the 1-m³ chamber. Although there is some curvature in the plotted inerting levels in the 1-m³ chamber, and even a minimum inerting concentration in the case of inerting with sodium bicarbonate, this curvature is not observed in the 20-L results.

In Figure 3.7 a concentration of 500 g/m³ of anthraquinone required 770 g/m³ of monoammonium phosphate to inert in the 1-m³ chamber, and 1333 g/m³ to inert in the 20-L chamber. These data correspond to a concentration of 60% inertant in the 1-m³ chamber and 73% inertant in the 20-L chamber. At a fuel concentration of 1000 g/m³, anthraquinone required 1111 g/m³ of monoammonium phosphate to prevent an explosion in the 1-m³ chamber (a relative inertant concentration of 53%). In the 20-L chamber a higher concentration of inertant, 2667 g/m³, was required. This is a relative concentration of 73%, the same relative inerting level as that observed at the lower fuel concentration.

As seen in Figure 3.8 at a concentration of anthraquinone of 250 g/m³, the inerting level in the 1-m³ chamber is 875 g/m³ (relative concentration of 78% inertant). The inerting level in the 20-L chamber for the same fuel concentration is 1833 g/m³ (relative concentration of 88% inertant). Comparison with similar data from Figure 3.7 indicates that in the 20-L chamber, as in the 1-m³ chamber, monoammonium phosphate is a more effective inerting agent than sodium bicarbonate. Although an MIC of 1700 g/m³ is observed (Figure 3.8) in the inerting envelope of anthraquinone with sodium bicarbonate in the 1-m³ chamber, a minimum inerting concentration is not seen in the 20-L chamber inerting curve using a 5-kJ ignition source.

Figures 3.9, 3.10 and 3.11 show the results of the inerting tests for cornstarch with monoammonium phosphate, sodium bicarbonate and limestone, respectively, as inertants in the 20-L and 1-m³ chambers. As also seen in the anthraquinone results, the inerting levels for cornstarch in the 20-L chamber, using a 5-kJ ignition source, are much greater than those observed in the 1-m³ chamber.

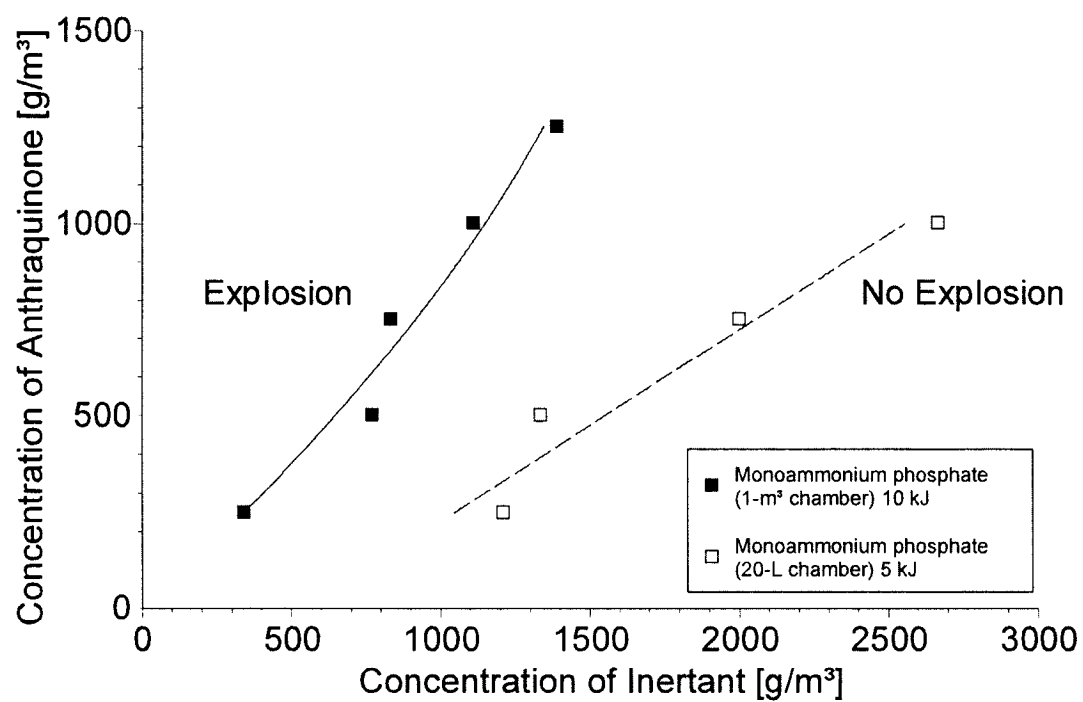


Figure 3.7: Comparison of 1-m³ and 20-L chamber inerting curves for anthraquinone using monoammonium phosphate as inertant.

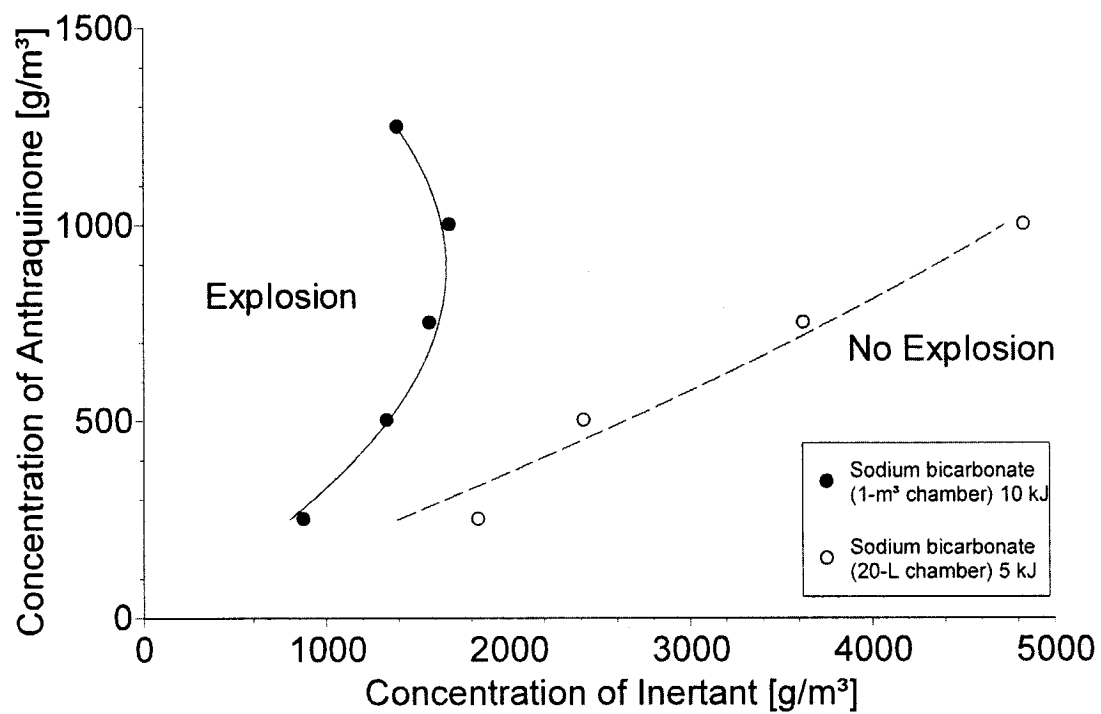


Figure 3.8: Comparison of 1-m³ and 20-L chamber inerting curves for anthraquinone using sodium bicarbonate as inertant.

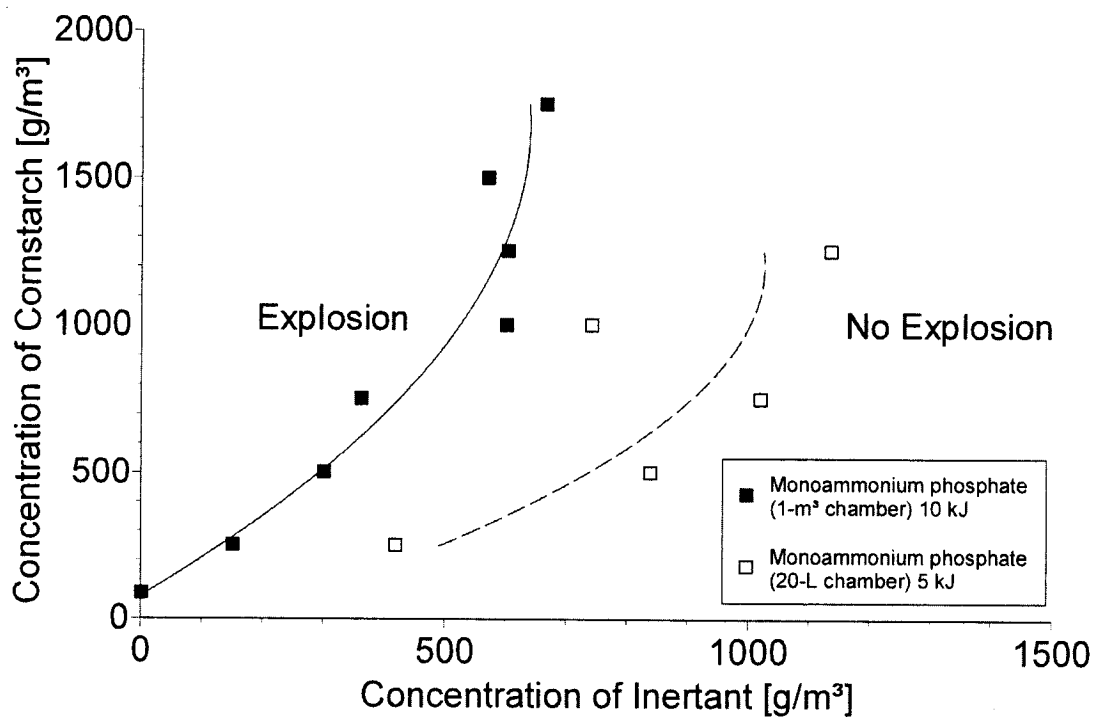


Figure 3.9: Comparison of 1-m³ and 20-L chamber inerting curves for cornstarch using monoammonium phosphate as inertant.

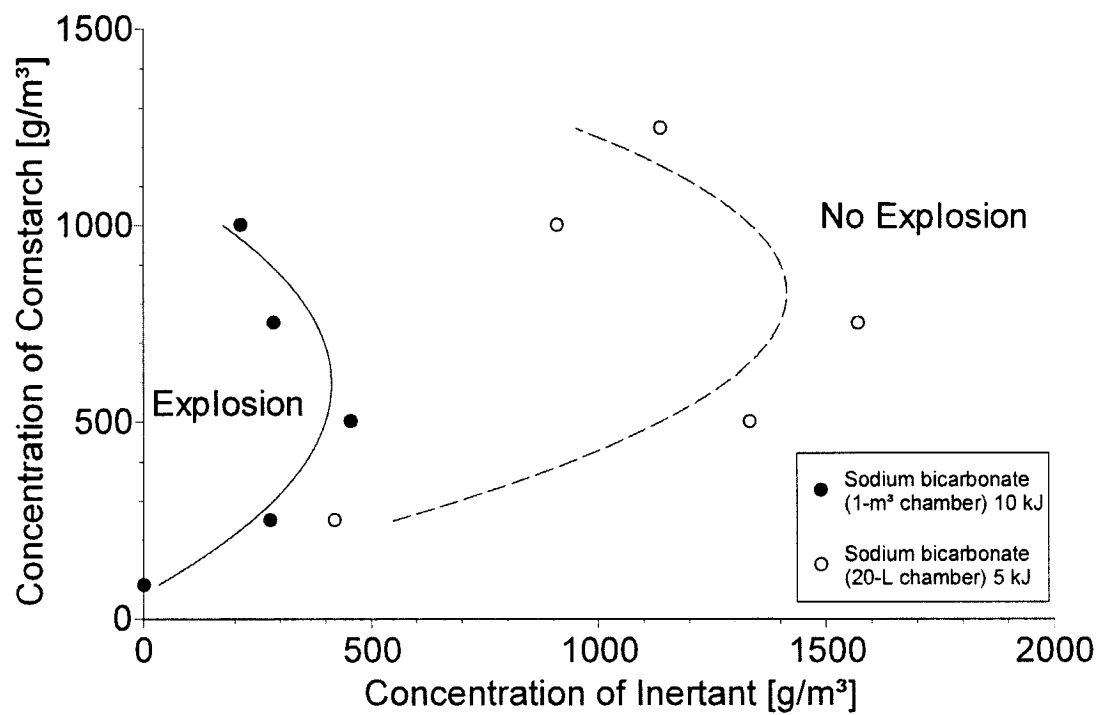


Figure 3.10: Comparison of 1-m³ and 20-L chamber inerting curves for cornstarch using sodium bicarbonate as inertant.

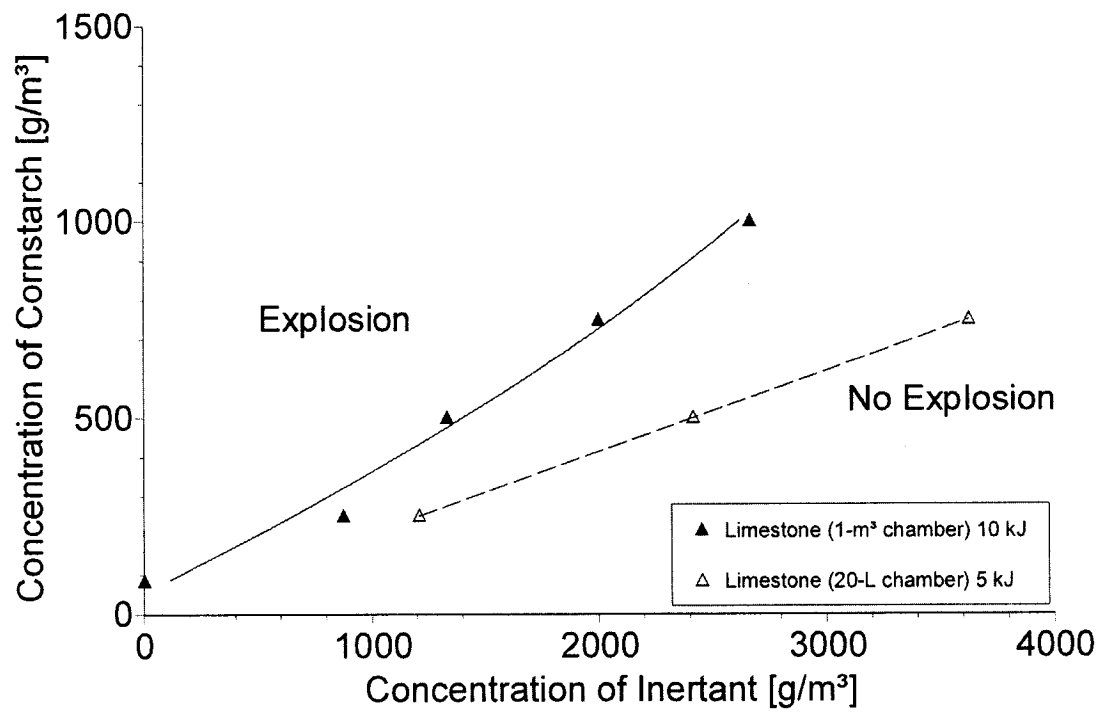


Figure 3.11: Comparison of 1-m³ and 20-L chamber inerting curves for cornstarch using limestone as inertant.

In Figure 3.9, which shows some curvature at high fuel concentrations in the 1-m³ chamber, there is a similar curvature in the 20-L chamber inerting envelope. The 1-m³ results, while not forming a complete envelope, approach an asymptote near 700 g/m³ of monoammonium phosphate. The 20-L inerting results have a similar curvature and appear to approach an asymptote near 1200 g/m³ inertant.

In Figure 3.10 a distinct envelope is observed for the inerting levels in both chambers. The MIC from the 1-m³ chamber inerting envelope is 450 g/m³. The MIC determined in the 20-L chamber, using a 5-kJ ignition source, is much greater at 1500 g/m³. As seen in Figure 3.11 for both the 1-m³ and 20-L volumes, the plots of the inerting level as a function of fuel concentration do not form an envelope over the concentration ranges tested.

Figure 3.12 shows the results of the inerting tests for Pittsburgh pulverized coal with monoammonium phosphate as inertant in the 20-L and 1-m³ chambers. As with the other carbonaceous dusts tested, the inerting level and the MIC are much greater in the 20-L chamber, using a 5-kJ ignition source, than those observed in the 1-m³ chamber. The MIC for the 1-m³ volume is approximately 100 g/m³; the 20-L MIC is significantly higher at about 700 g/m³. In both chambers there is a distinct curvature of the line depicting the general trend of the interpolated inerting levels. This curvature is an indication that higher concentrations of fuel present in the combustion chamber require less inertant to prevent an explosion than intermediate concentrations of fuel.

On a relative basis, this concentration level dependence can be seen in the quantity of inertant required to prevent an explosion at 250 g/m³, at the low end, and 1500 g/m³ at the upper level of fuel loading. At low fuel concentrations the relative concentration of material required to prevent an explosion is 60% in the 20-L chamber using a 5-kJ igniter to initiate combustion in the vessel. At the higher fuel concentration the relative amount of inert material in the total mixture required to prevent an explosion is only 25%.

Figures 3.13 and 3.14 show the results of the inerting tests for Pittsburgh pulverized coal with sodium bicarbonate and limestone, respectively, as inertants in the 20-L and 1-m³ chambers. As with the inerting of Pittsburgh pulverized coal with monoammonium

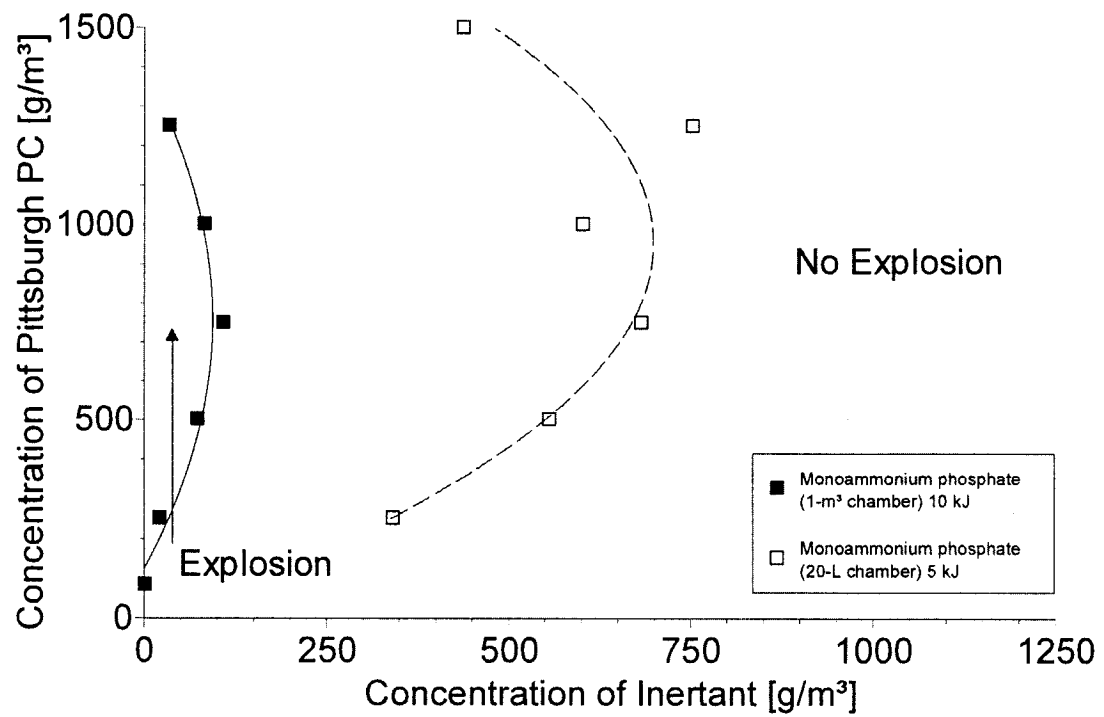


Figure 3.12: Comparison of 1-m³ and 20-L chamber inerting curves for Pittsburgh pulverized coal using monoammonium phosphate as inertant.

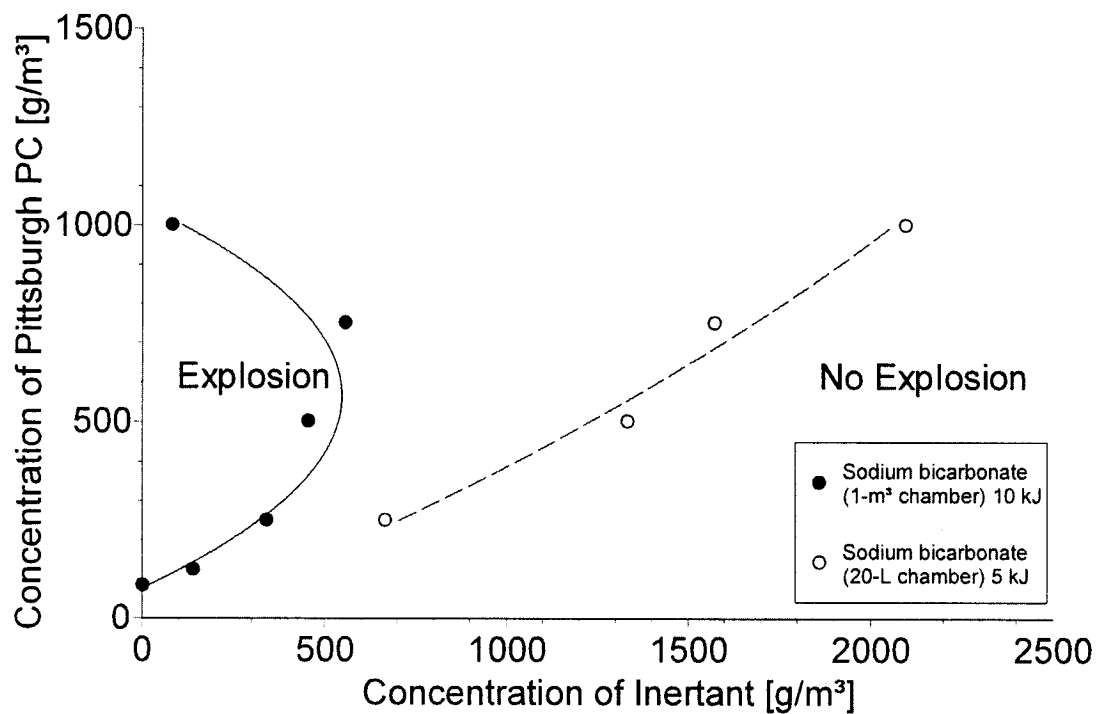


Figure 3.13: Comparison of 1-m³ and 20-L chamber inerting curves for Pittsburgh pulverized coal using sodium bicarbonate as inertant.

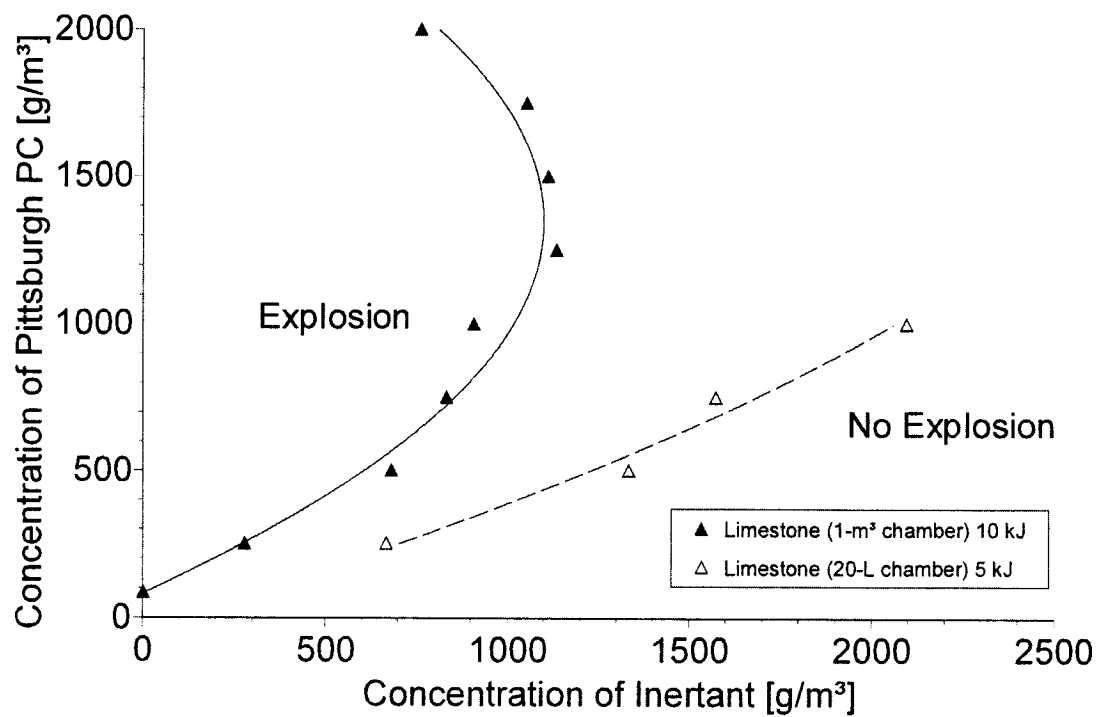


Figure 3.14: Comparison of 1-m³ and 20-L chamber inerting curves for Pittsburgh pulverized coal using limestone as inertant.

phosphate, the inerting levels determined in the 20-L chamber, using a 5-kJ ignition source, are much greater than those measured in the 1-m³ chamber. However, unlike Pittsburgh pulverized coal inerting with monoammonium phosphate, the lines used to depict the trends observed in the interpolated inerting levels do not curve sufficiently in the concentration ranges tested to form a distinct envelope in the 20-L chamber. Inerting envelopes are, however, formed in the 1-m³ chamber.

Figures 3.15 and 3.16 show the results of the inerting tests for polyethylene with monoammonium phosphate and sodium bicarbonate, respectively, as inertants in the 20-L and 1-m³ chambers. Again, the inerting level is much greater in the 20-L than the 1-m³ volume.

3.5.2 Influence of Ignition Energy

As previously mentioned, the initial choice of using a 5-kJ ignition source in the smaller chamber to determine the inerting level was due to the good agreement this energy produced with mine-scale results (Dastidar *et al.* (1997)). Our more recent work (Dastidar *et al.*, (1998c), Dastidar *et al.*, (2001)) has shown that for coal dust, the use of a 5-kJ ignitor tends to result in higher inerting levels in the 20-L chamber than those observed in the 1-m³ chamber. Additionally, other researchers have found that lower ignition energies are required to produce minimum explosible concentration (MEC) values in the 20-L chamber comparable to results obtained from larger scale experiments (Cashdollar and Chatrathi (1992)). The MEC is another limit flame condition similar to the MIC. In this section, we therefore report on the comparison of inerting levels between the 20-L and 1-m³ volumes when the applied ignition energy in the 20-L chamber is varied.

Figure 3.17 depicts the inerting envelope for anthraquinone using sodium bicarbonate as an explosion-mitigating agent. The 1-m³ data and the 20-L data using a 5-kJ ignition source are from Figure 3.8. However, in the current figure data from inerting experiments conducted in the 20-L chamber using a 1-kJ ignition source are also given. The use of the lower ignition energy to initiate combustion significantly reduces the inerting level in the 20-L chamber. For example, at a fuel concentration of 500 g/m³ the 20-L inerting level

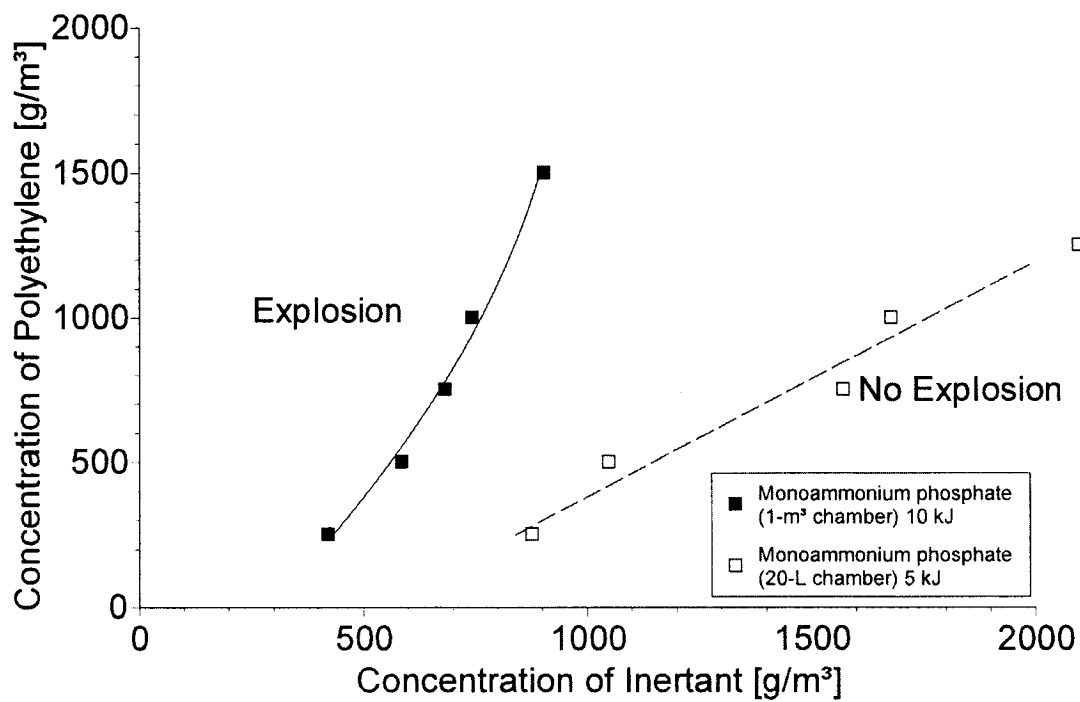


Figure 3.15: Comparison of 1-m³ and 20-L chamber inerting curves for polyethylene using monoammonium phosphate as inertant.

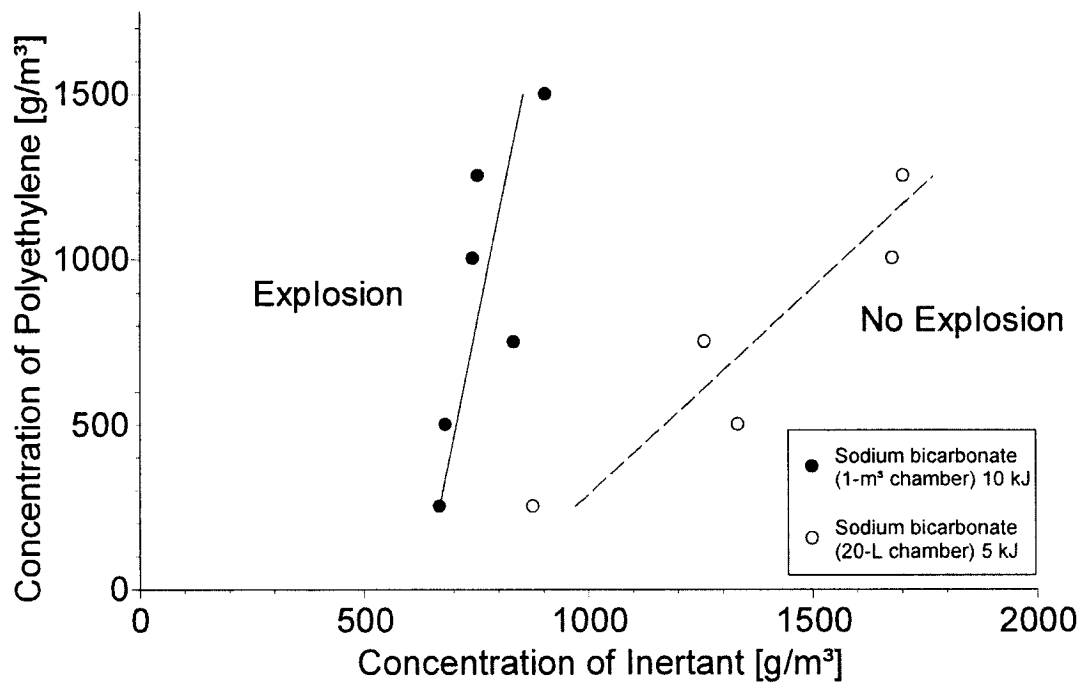


Figure 3.16: Comparison of 1-m³ and 20-L chamber inerting curves for polyethylene using sodium bicarbonate as inertant.

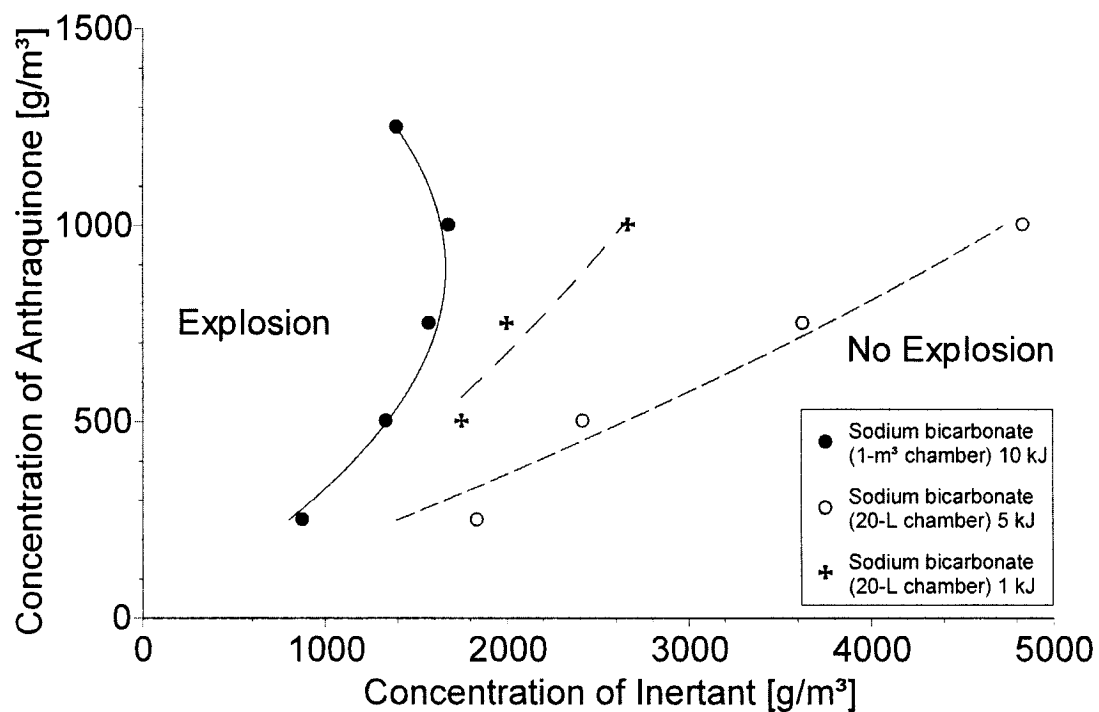


Figure 3.17: Comparison of 1-m³ and 20-L chamber inerting curves at different ignition energies for anthraquinone using sodium bicarbonate as inertant.

was reduced from 2416 g/m³ to 1750 g/m³, which is closer to the 1-m³ value of 1333 g/m³. The inerting level decrease is much greater at higher fuel concentrations. At 1000 g/m³ the inerting level in the 20-L chamber using a 5-kJ ignition source is 3625 g/m³. This level is decreased to 2000 g/m³ when a 1-kJ igniter is used in the chamber.

This phenomenon may be due to two factors. First, the squib ignitors are not point ignition sources but release energy volumetrically. The 5-kJ igniter behaves as a multipoint volumetric ignition source occupying about one-third of the 20-L volume of the smaller chamber (Zhen and Leuckel (1997)). This can lead to overdriving of the smaller chamber at limit flame conditions where combustion of the dust particles within the large flame volume generate enough heat to change the test conditions in the chamber, namely temperature and pressure. This elevated temperature and pressure condition can render combustible a fuel/inertant mixture that is noncombustible under ambient conditions. Additionally, the burning of the fuel in the flame volume without true propagation can increase the pressure of the chamber so as to exceed the limit explosibility criterion of 1 bar(g). The lower strength 1-kJ ignitor would not occupy as much volumetric space and therefore not be able to change the dust cloud conditions as greatly, thereby reducing or eliminating overdriving of the smaller chamber.

The second factor that may contribute to this phenomenon involves oxygen diffusion to the reaction zone in dense dust cloud conditions. As previously noted, under dense cloud conditions a burning particle of fuel may rob its neighbor of oxygen, thus inhibiting propagation of flame to it. The larger ignitor ejects more hot particles of pyrotechnic material to a greater number of multiple locations in the chamber. This induced combustion at multiple points does not rob neighboring particles of oxygen to as great an extent as would a lower energy ignitor. The hot ejected material from the lower energy ignitor would be more concentrated in the center of the vessel and would be “less multipoint” in nature. This localized combustion, under dense cloud conditions, may lead to flame quenching by oxygen starvation of the flame zone.

Even with the lower ignition energy, the formation of a distinct inerting envelope and subsequent MIC as seen in the 1-m³ chamber is not observed in the 20-L chamber (Figure

3.17). The good agreement in the inerting level observed between the 20-L chamber using a 5-kJ ignition source and mine scale results may be due to overdriving in the small chamber, thus simulating the influence of pressure piling that is observed in the mine-scale tests. Pressure piling occurs during flame propagation in structures that have a high L/D ratio (Kumar *et al.*, (1992)).

Figure 3.18 shows the inerting curve for Pittsburgh pulverized coal using sodium bicarbonate as an inertant. The data of note are the inerting results for the 20-L chamber using a 1-kJ ignitor. The trend observed in Figure 3.17 is also seen here; the inerting levels at low concentrations more closely approximate 1-m³ inerting results. For example, at 250 g/m³ of fuel the 20-L chamber result using a 1 kJ ignitor is similar to the 1-m³ level - 278 g/m³ and 340 g/m³, respectively. The difference in the inerting levels from the two chamber volumes increases as the fuel loading increases. Unlike the 1-m³ chamber, no distinct envelope is formed in the 20-L chamber, even with the 1-kJ ignitor. The trend does make it appear as if an envelope is being formed; however, the high inerting level at 1250 g/m³ of fuel prevents the enclosure from developing completely.

Figure 3.19 shows the inerting of cornstarch using sodium bicarbonate. Unlike Figures 3.17 and 3.18, an envelope and MIC are formed in the 20-L chamber when testing with the lower ignition energy (as well as with 5 kJ). Tests conducted in the 20-L chamber using a 1-kJ ignition source produced inerting results similar to those measured in the 1-m³ chamber. Decreasing the ignition energy in the 20-L chamber from 5 kJ to 1 kJ lowered the apparent MIC from 1500 g/m³ to 500 g/m³; the latter value is comparable to the 1-m³ MIC value of 450 g/m³.

Figure 3.20 shows the inerting envelope for Pittsburgh pulverized coal using monoammonium phosphate as an inertant. Several additional ignition energies were tested in the 20-L chamber: 2.5, 1, and 0.5 kJ. Clearly, decreasing the ignition energy from 5 kJ results in inerting levels similar to those observed in the 1-m³ chamber. In several instances, the inerting level plotted on the graph for the 20-L chamber, using a 0.5 kJ igniter, overlaps data points from the 1-m³ chamber.

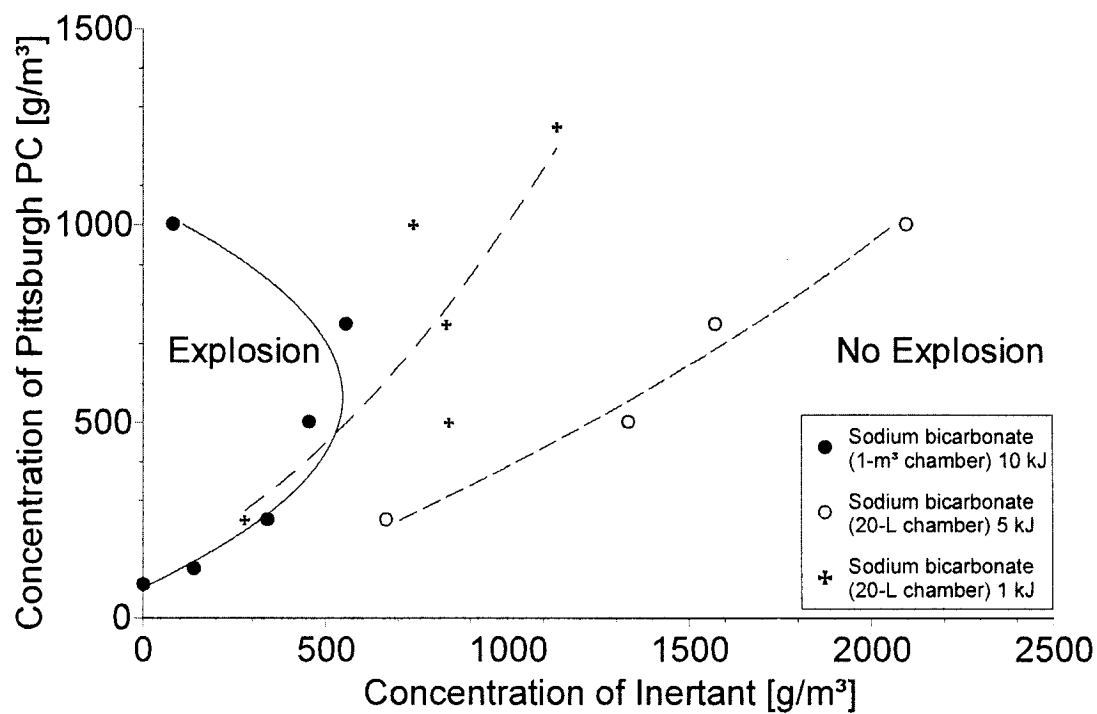


Figure 3.18: Comparison of 1-m³ and 20-L chamber inerting curves at different ignition energies for Pittsburgh pulverized coal using sodium bicarbonate as inertant.

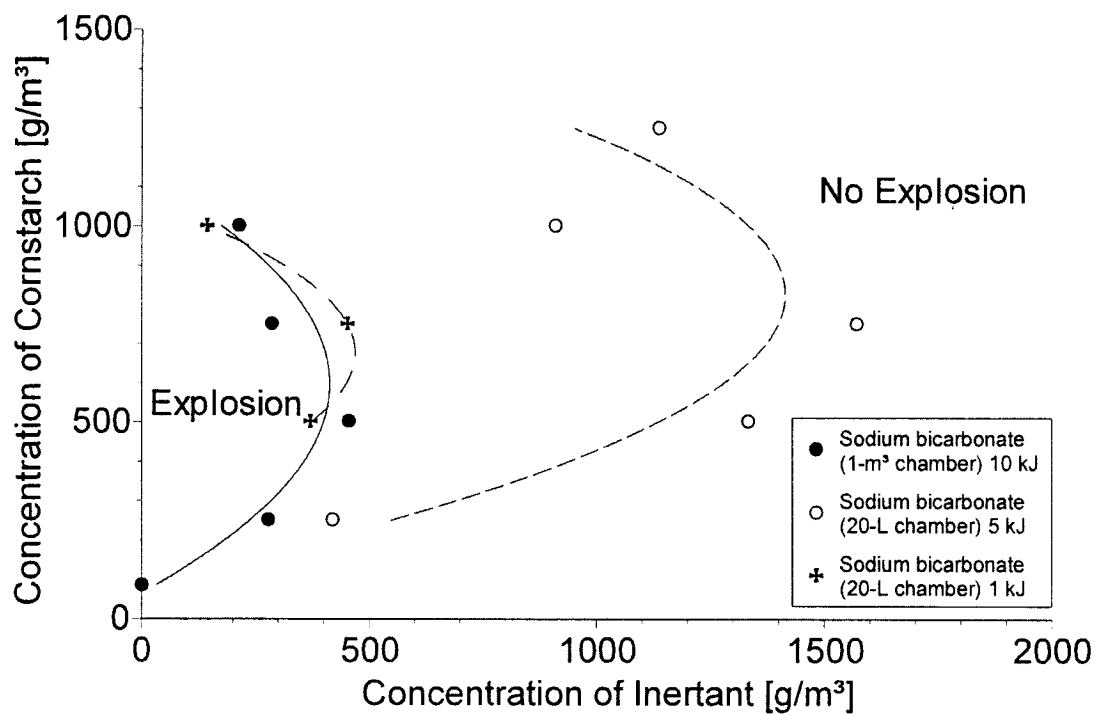


Figure 3.19: Comparison of 1-m³ and 20-L chamber inerting curves at different ignition energies for cornstarch using sodium bicarbonate as inertant.

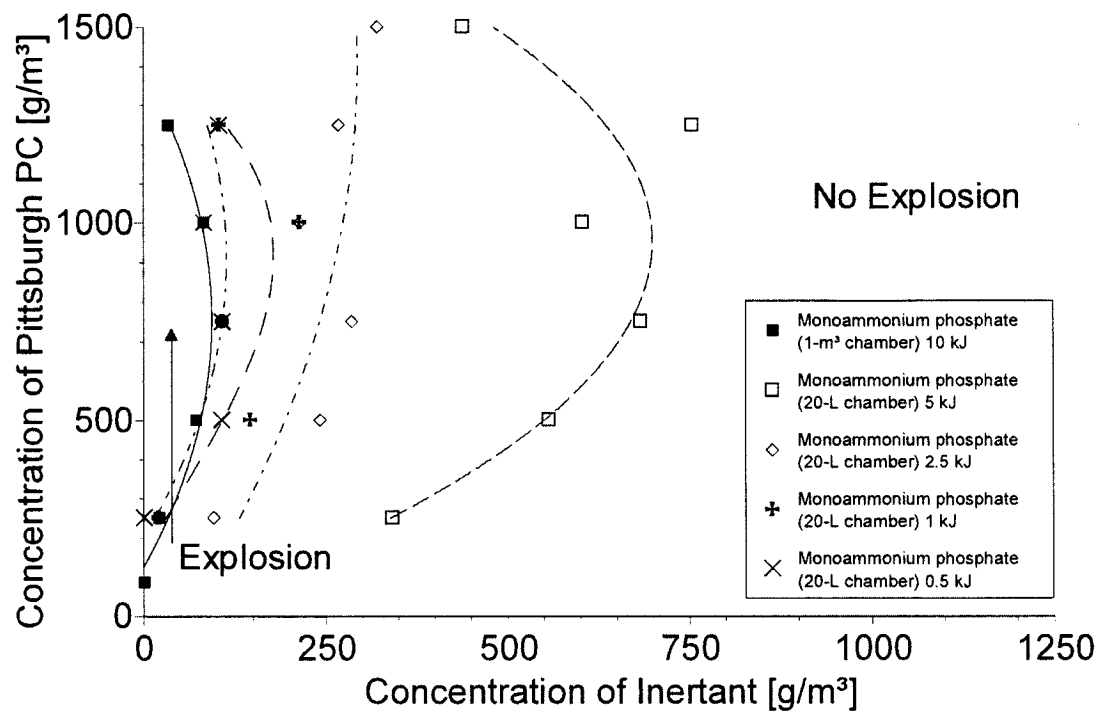


Figure 3.20: Comparison of 1-m³ and 20-L chamber inerting curves at different ignition energies for Pittsburgh pulverized coal using monoammonium phosphate as inertant.

It is readily apparent that the ignition energy required to produce inerting results in the 20-L chamber similar to a 1-m³ volume is dependant on the material being tested. Aluminum, a hot burning metal, did not need a reduction in the ignition energy to produce similar results in both chambers. On the other hand, the carbon-based dusts clearly did. This requirement for low ignition energies (0.5 - 1 kJ) in the 20-L chamber for carbonaceous dusts is an indication that ignition energy density is an important consideration in testing for inerting levels. The standard ignition strength used in the 1-m³ chamber produces an ignition energy density in the chamber of 10 kJ/m³. When using a 5 kJ ignitor for inerting level testing in the 20-L chamber, an ignition strength which gives good agreement with mine-scale experimental results, the energy density is 250 kJ/m³. Decreasing the ignition energy in the smaller chamber brings the energy density closer to that existing in the larger chamber. A 1-kJ ignitor produces a nominal energy density of 50 kJ/m³ in the 20-L chamber, a 0.5-kJ ignitor produces half that value. Both these lower energies produce energy density values of the same order of magnitude as that in the 1-m³ chamber.

When reviewing this dissimilitude between 20-L, 1-m³ and mine-scale inerting levels (for coal dust) it appears that energy density, in conjunction with vessel geometry, must be considered. For vessels with high L/D ratios where flame acceleration due to pressure piling can occur, as in a mine gallery, a high energy density is required in the 20-L chamber to produce similar inerting results. In chambers with lower L/D ratios where the propagating flame front in the burning dust cloud will reach the vessel walls at approximately the same time (making allowances for buoyancy and turbulence factors), a lower ignition energy density is required.

As demonstrated by the data in Figures 3.19 and 3.20, the MIC observed in the 1-m³ chamber can be reproduced in the 20-L chamber when low ignition energies are used for inerting level testing. This fact permits the use of the smaller vessel, with attention to experimental conditions, in determining the amount of inert matter that will prevent an explosion regardless of fuel concentration. This quantity of inertant, when mixed intimately together with the fuel, can be used as the zero-time suppressant requirement (Figure 3.2). This suppressant quantity can then be of assistance in constructing a

complete suppression scheme. The use of the smaller 20-L chamber in determining this value will result in time, monetary and labor savings. Also, an important point to note when examining the inerting results is that the relative effectiveness of the inerting material in mitigating the fuel dust explosion in the 1-m³ chamber is maintained in the 20-L chamber. Sodium bicarbonate is more effective than monoammonium phosphate in mitigating aluminum dust explosions and monoammonium phosphate is more effective for carbonaceous dusts in both chambers.

Table 3.3 summarizes the minimum inerting concentration results from both the 1-m³ chamber and the 20-L Siwek chamber. The cases of cornstarch inerting with monoammonium phosphate and sodium bicarbonate, and Pittsburgh pulverized coal dust with monoammonium phosphate, show the presence of an MIC in both chambers. For the cases where an MIC was observed in the 1-m³ volume but not in the 20-L volume (anthraquinone and Pittsburgh pulverized coal inerted with sodium bicarbonate), a large reduction in inerting level was observed when the ignition energy was decreased from 5 kJ to 1 kJ. Further reduction of the ignition source to 0.5 kJ (not tested) may result in the formation of an MIC. Decreasing the ignition source from 5 kJ for testing of Pittsburgh pulverized coal dust with limestone may also lead to the formation of an MIC for this material since an inerting concentration level dependence on ignition strength has already been observed (Dastidar *et al.*, (1997)).

Table 3.3: Summary of MIC results for various fuel and inertant combinations.

Fuel	Inertant	Existence of Minimum Inerting Concentration (MIC) (Value g/m ³)				
		1-m ³ Chamber* 10-kJ Ignitor	20-L Chamber 5-kJ Ignitor	20-L Chamber 2.5-kJ Ignitor	20-L Chamber 1-kJ Ignitor	20-L Chamber 0.5-kJ Ignitor
Aluminum	Monoammonium Phosphate	No	No			
	Sodium Bicarbonate	No	No			
Anthraquinone	Monoammonium Phosphate	No	No			
	Sodium Bicarbonate	Yes (1700 g/m ³)	No		No	
Cornstarch	Monoammonium Phosphate	Effective (650 g/m ³)	Effective (1150 g/m ³)			
	Sodium Bicarbonate	Yes (450 g/m ³)	Yes (1500 g/m ³)		Yes (500 g/m ³)	
	Limestone	No	No			
Pittsburgh Pulverized Coal	Monoammonium Phosphate	Yes (100 g/m ³)	Yes (700 g/m ³)	Effective (300 g/m ³)	Yes (150 g/m ³)	Yes (100 g/m ³)
	Sodium Bicarbonate	Yes (600 g/m ³)	No		No	
	Limestone	Yes (1100 g/m ³)	No			
Polyethylene	Monoammonium Phosphate	Effective (900 g/m ³)	No			
	Sodium Bicarbonate	Effective (900 g/m ³)	No			

3.6 CONCLUSION

The smaller 20-L chamber can be used to produce inerting levels similar to those observed in the 1-m³ chamber. For carbonaceous dusts, this requires performing explosibility tests using ignition energies of 0.5 to 1 kJ. The only metal dust tested in the current study produced similar inerting levels in the 20-L chamber as in the 1-m³ chamber when using a stronger 5-kJ ignition source.

The dependence of the inerting level on fuel concentration observed in the 1-m³ vessel was observed to a lesser extent in the 20-L chamber. However, for some dusts which showed a distinct MIC in the 1-m³ chamber, the presence of an MIC of similar magnitude was demonstrated when using low strength ignitors. This permits the use of the 20-L chamber in MIC determination for some materials with careful consideration of test conditions such as ignition energy.

3.7 FUTURE WORK

The value of conducting explosion mitigation experiments in a 20-L chamber is to minimize the time and expense of inerting level and MIC determination over that in the 1-m³ chamber. Further minimization of design expenses may be achieved by using a mathematical model to estimate or predict the inerting level and, specifically, the minimum inerting concentration. To that end we are currently working on a report of the results of a such a model based on the concept of calculated adiabatic flame temperature.

3.8 ACKNOWLEDGMENTS

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4 COMPARISON OF COAL DUST INERTING IN AN INTERMEDIATE-SCALE 1-M³ SPHERICAL CHAMBER AND A SMALL-SCALE 20-L SPHERICAL CHAMBER

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A. G. Dastidar, P. R. Amyotte, J. Going and K. Chatrathi, "*Inerting of coal dust explosions in laboratory- and intermediate-scale chambers*", **Fuel**, vol. 80, pp. 1593-1602, 2001*. The text and figures in this section are identical to that of the published paper with the exception that section numbers have been added, and figure and table numbers have been changed, to reflect the thesis format.

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4.1 ABSTRACT

Experiments were performed to compare intermediate-scale (1-m^3) and laboratory-scale (20-L) coal dust inerting results. Intermediate-scale inerting levels appear to be lower than laboratory-scale values. This can possibly be attributed to the use of a strong ignition source to initiate the test, which may have overdriven the explosions in the smaller test vessel. Previously reported agreement between the smaller test vessel and full-scale experiments may be due to overdriving in the 20-L chamber, leading to high inerting levels similar to those encountered in full-scale tests due to flame acceleration. Additionally, a reduction in the particle size of the rock dust used for inerting has been found to influence the quantity required to prevent an explosion in the 1-m^3 chamber. This agrees with previous work conducted in smaller chambers.

4.2 INTRODUCTION

The presence of dust in an underground coal mine can be a serious explosion hazard. During the course of mining operations, pockets of methane can accumulate at the mine face. An ignition source can then ignite the methane causing a gas explosion. As this explosion travels out from the face, the resulting pressure wave disperses any coal dust that may be deposited on the roof, walls, and floors of the gallery. The gas explosion then acts as an ignition source for the coal dust, creating a dust explosion. The dust explosion then progresses down the length of the gallery generating turbulence. This can result in pressure piling and flame acceleration that will further increase the violence of the explosion.

One of the ways to mitigate the explosion hazard posed by coal dust is to spread rock dust in mine galleries. The rock dust acts as a thermal inhibitor; it absorbs heat from the flame front of an explosion and quenches its propagation. For rock dusting to be effective, however, it is important to determine the amount of rock dust required to prevent an explosion. This determination can be carried out in mine-scale experiments (Weiss *et al.* (1989), Sapko *et al.* (1989), Sapko *et al.* (2000)), which can be expensive and time-consuming. As a possible alternative, laboratory- and intermediate-scale test equipment can also be used. Two types of laboratory-scale chambers that are widely used are the 20-L NIOSH PRL (National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory¹) chamber (Cashdollar and Hertzberg, (1985)) and the higher turbulence 20-L Siwek chamber (Siwek, (1977)).

Previous work by Dastidar *et al.* (1997) has demonstrated the utility of the 20-L volume in determining rock dust inerting levels. They have shown that experimental inerting data from a 20-L Siwek chamber are in good agreement with inerting results obtained from the NIOSH PRL Lake Lynn Experimental Mine (LLEM). Mine-scale inerting levels of Pittsburgh and Pocahontas pulverized coals were reported to be 79 % and > 68 %, respectively.

¹ formerly the United States Bureau of Mines, Pittsburgh Research Center (USBM PRC)

respectively (Weiss *et al.* (1989), Sapko *et al.* (2000), Cashdollar and Hertzberg, (1989)); inerting results from the smaller chamber were 78 % for Pittsburgh pulverized coal and 74 % for Pocahontas pulverized coal using a 5-kJ ignition source (Dastidar *et al.* (1997)). This relatively good agreement between large- and small-scale inerting results prompted the current interest in comparing small-scale inerting results with intermediate-scale experiments involving coal dust.

A common intermediate-scale vessel used for dust explosion testing is a 1-m³ chamber. This vessel volume, in conjunction with an appropriate turbulence level, is widely used for standard explosibility testing such as determination of the maximum rate of pressure rise to determine vent sizes. It is also widely used to determine the maximum overpressure, minimum explosible concentration and limiting oxygen concentration. The possibility exists that this vessel may also be used to determine the rock dust inerting level for coal dust explosions.

The current work focuses on the use of an intermediate-scale vessel for inerting level determination of coal dust explosions using rock dust. The objective of this work was to compare the inerting effectiveness of rock dust in a 1-m³ chamber with that in a 20-L Siwek chamber from our previous work (Dastidar *et al.* (1997)) and mine-scale galleries (Weiss *et al.* (1989), Sapko *et al.* (1989), Sapko *et al.* (2000)). Effects of ignition energy, rock dust particle size, and coal dust concentration on the amount of rock dust required to prevent an explosion were investigated.

4.3 EXPERIMENTAL

Samples of coal from the Prince mine were obtained from the Cape Breton Development Corporation (CBDC). At Dalhousie, the coal was ground and sieved to produce a coarse fraction having a broad particle size distribution (CBDC mine-size coal). A sample of Pittsburgh pulverized coal dust was obtained from the NIOSH PRL and was tested as received. This is the same material used by the NIOSH PRL for their full-scale and laboratory-scale experiments. This material was also used in our previous study (Dastidar *et al.*, (1997)).

Particle size measurement of the pulverized coal was made using a Malvern Instruments 2600 Series analyzer based on the principle of laser diffraction; the particle size distribution of the coarse fraction was determined by sieve analysis. The results of the particle size analyses are given in Table 4.1 in which the arithmetic volume or mass mean diameter, D_w , is shown. Table 4.1 also shows the particle size distributions of the rock dusts used in the experiments. Proximate analyses of the coals are given in Table 4.2. To prevent loss of volatiles and surface oxidation, the coal dust was kept in air-tight containers. To facilitate comparison between previous work and current experiments, the particle size and proximate analysis data from Dastidar *et al.* (1997) have also been included in Tables 4.1 and 4.2.

Table 4.1: Particle size analyses of coal and rock dusts.

Dust	< 500 μm [wt %]	< 125 μm [wt.%]	< 75 μm [wt.%]	< 45 μm [wt.%]	< 20 μm [wt.%]	D_w [μm]
CBDC Mine-Size Coal	60	22	15	11	6	393
CBDC Mine-Size Coal †	84	21	15	11	6	299
Pittsburgh Pulverized Coal	100	93	69	42	14	60
CBDC Regular Dolomite	100	86	69	50	30	50
CBDC Regular Dolomite †	100	87	65	45	25	65
NIOSH PRL Limestone	100	94	78	65	49	41
AIM Baghouse Limestone	100	96	90	80	57	26
AIM Baghouse Limestone †	100	100	99	96	86	12
AIM Regular Limestone †	100	98	91	78	49	31

† Material used in previous work (Dastidar *et al.* (1997))

Table 4.2: Proximate analyses of coal dusts.

	CBDC Mine-Size Coal	CBDC Mine-Size Coal [†]	Pittsburgh Pulverized Coal
Moisture (weight %)	2.9	1.4	1.4
Ash (weight %)	27.5	3.7	5.8
Volatile Matter (weight %)	37.6	34.3	36.4
Fixed Carbon (weight %)	32.0	60.7	56.4

[†] Material used in previous work (Dastidar *et al.* (1997))

Three types of rock dust were used for experimentation. A sample of dolomite was obtained from the CBDC. Limestone was obtained from the NIOSH PRL (the same material they use for their full-scale and laboratory-scale testing). Fine limestone collected from the milling baghouse at the Point Aconi (Nova Scotia) power plant was obtained from Atlantic Industrial Minerals (AIM), Nova Scotia. The results of calcium/magnesium compositional analyses of the rock dusts are shown in Table 4.3. Again, to facilitate comparison between previous work and current experiments, the compositional analyses of the rock dusts from Dastidar *et al.* (1997) have also been included in this table.

Table 4.3: Compositional analyses of rock dusts.

Type of Rock Dust	CaCO ₃ [wt.%]	MgCO ₃ [wt.%]
CBDC Regular Dolomite	61.8	32.8
CBDC Regular Dolomite [†]	55.8	41.0
NIOSH PRL Limestone	88.9	1.0
AIM Baghouse Limestone	98.0	0.9
AIM Baghouse Limestone [†]	85.7	0.9
AIM Regular Limestone [†]	84.9	0.9

[†] Material used in previous work (Dastidar *et al.* (1997))

To compare the influence of scale on the inerting level of dust explosions, experiments were performed in two different vessels: the Fike 1-m³ vessel located in Blue Springs, MO and the 20-L Siwek explosion chamber located in Halifax, Nova Scotia. The Fike 1-m³ vessel is a spherical explosion chamber designed to gather explosion severity and explosion protection testing data. A schematic of the apparatus is shown in Figure 4.1. For inerting tests, both combustible dust and inert solid are premixed and then introduced into the vessel. The vessel is made of two 122-cm internal diameter, 0.95-cm thick

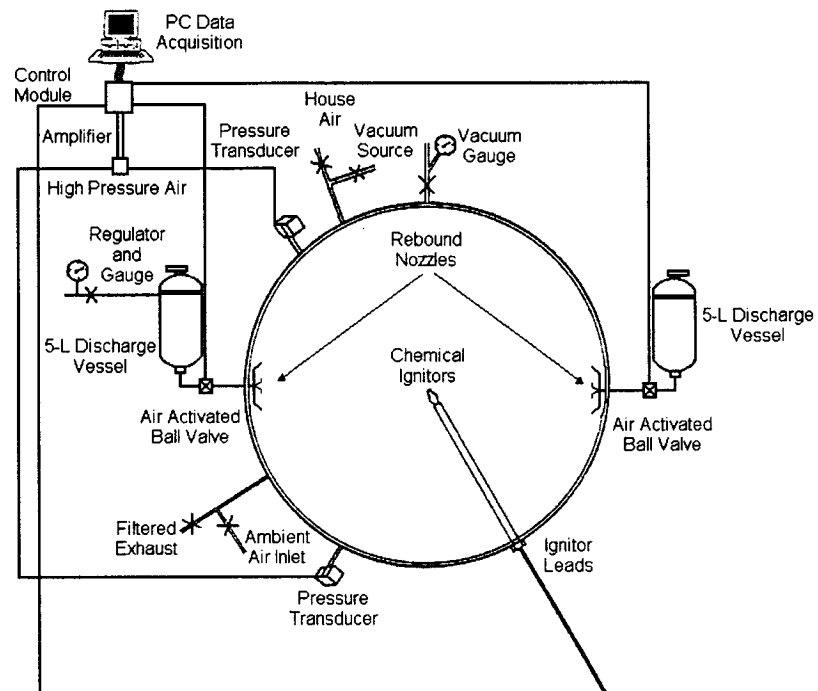


Figure 4.1: Schematic diagram of Fike spherical 1-m³ chamber.

carbon steel hemispherical sections that can be separated to allow access to the interior. These two halves of the sphere are connected by twelve 51-mm diameter bolts. The vessel has a design pressure of 21 bar(g).

The dust injection system consists of two 5-L discharge cylinders, each with a ball valve and a Kühner type rebound nozzle for dust dispersion. To create a combustible dust cloud in the 1-m³ chamber, a weighed amount of premixed dust and inertant mixture is placed equally into both 5-L cylinders. The 5-L discharge cylinders are pressurized to 19.3 bar(g) each, and the 1-m³ vessel is partially evacuated to 0.88 bar(a). The ball valves between the discharge cylinders and the rebound nozzles are opened by using a pneumatic actuator. The air and the dust in the discharge cylinders enter the 1-m³ vessel through the rebound nozzles to create the dust cloud. This dispersion process increases the vessel pressure from 0.88 bar(a) to 1 bar(a).

The dust explosions are initiated by chemical ignitors triggered 0.7 s after the activation of the ball valve. The chemical ignitors are manufactured by Sobbe and contain 40 % zirconium, 30 % barium nitrate and 30 % barium peroxide. An ignitor with a stored energy of 5 kJ has 1.2 grams of this mixture. The energy is released in about 10 ms. The discharge of a single 5-kJ ignitor by itself will cause the pressure to rise by 11 mbar in the 1-m³ chamber.

Two variable reluctance pressure transducers manufactured by Validyne (model DP 215) are used to monitor the progress of the explosions. The transducers in combination with their amplifier electronics have a sufficiently fast response time to provide pressure measurements with a 1 ms resolution. A Metrabyte data acquisition board is used in conjunction with a personal computer to gather the pressure data as a function of time and to control the experiments. Two D/A channels on the data acquisition board are used to activate the ball valves and to initiate the chemical ignitors. Software programming allows control of the delay time between activation of the valves and ignition. It also allows the conversion of the analogue signals into absolute pressure measurements.

Previously, the 1-m³ chamber had only one discharge chamber and dispersion ring. The dispersion time and turbulence level were comparable to those in the European 1-m³

chambers (Bartknecht, 1989). This is the turbulence level in ASTM Standard E1226, ISO Standard 6184/1, NFPA Guide 68, and VDI Standard 3673 to determine the maximum rate of pressure rise to determine vent sizes. However, since the nature of inerting experiments requires greater quantities of material (dust and inertant) to be injected into the explosion chamber, the apparatus has been modified to use two dispersion chambers. The ignition delay time has been increased from 0.55 s to 0.7 s and the discharge chamber pressurization has been decreased from 32 bar(g) to 19.3 bar(g) to maintain similar turbulence levels. This procedure is recommended by Bartknecht (1989).

The explosion parameters (overpressure and rate of pressure rise) of the pure coal dusts were determined as a function of concentration. This was achieved by varying the amount of dust placed in the 5-L discharge chambers. The effect of inertant was then determined for each fuel concentration by measuring the explosion parameters as inertant was added to the mixture. To produce a homogenous and uniform dust cloud in the 1-m³ chamber, the inertant and fuel dusts were premixed and then placed into the two discharge chambers in equal quantities.

To determine the influence of scale on the inerting level, experiments were also performed in a 20-L Siwek chamber. A schematic diagram of the chamber and auxiliary equipment is shown in Figure 4.2. The spherical test chamber has a volume of 20 L and is made of stainless steel with a maximum allowable working pressure of 20 bar. The vessel is surrounded by a water jacket which is used to control the initial temperature of the test chamber. The top access cover is fitted with ignition leads. Sobbe chemical ignitors, similar to those used in the 1-m³ chamber, are connected to the ignition leads. (Different ignitors are used for different ignition energies.)

The desired amounts of fuel dust and inert dust for a given experiment are mixed and placed in the dust storage chamber (volume of 0.6 L). The ignitors are attached to the ignition leads and the test chamber is sealed and partially evacuated to 0.4 bar(a). The computer control program is then initiated and the dust storage chamber pressurized to 20 bar(g) with extra dry compressed air. The computer then opens the solenoid valve between the dust storage chamber and the test chamber, dispersing the air and dust

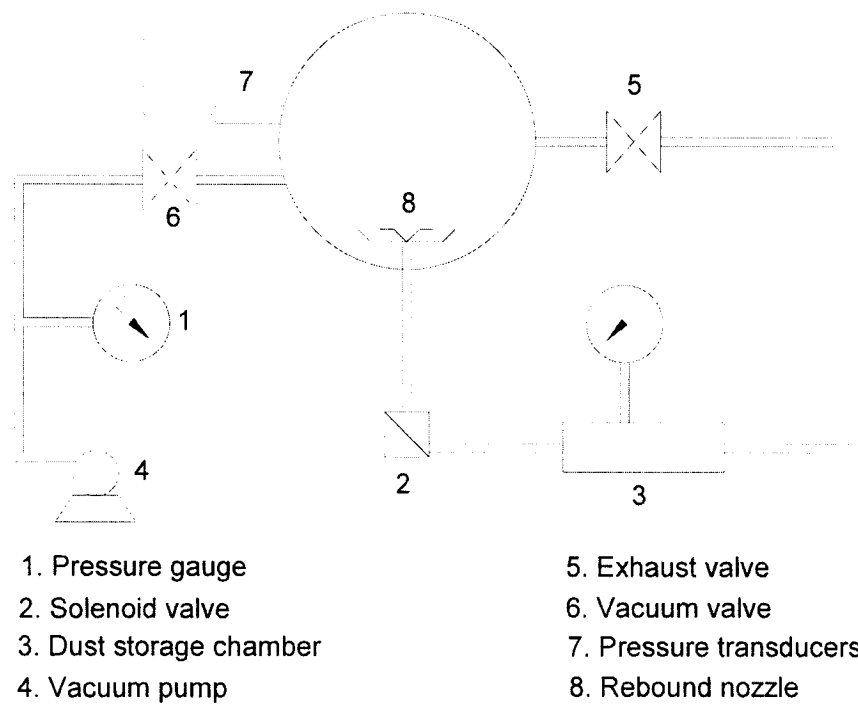


Figure 4.2: Schematic diagram of 20-L Siwek chamber.

mixture into the test chamber through a Kühner rebound nozzle and raising the chamber pressure from 0.4 bar(a) to 1 bar(a).

The computer then energizes the ignition source after a time delay of 60 ms. The computer records the pressure-time history of the explosion using two piezoelectric transducers installed flush with the interior of the chamber. The pressure-time trace provides the maximum overpressure (P_{ex}), the maximum overpressure due to the explosion of the dust mixture (P_m) using a correction algorithm to compensate for the pressure increase from the ignitor, and the maximum rate of pressure rise $((dP/dt)_m)$ for a given test.

The experimental test matrix is given in Table 4.4. The criterion used for an explosion in both vessels was an overpressure of 2 bar(a). Repeat testing was performed, when warranted, for experiments with the lowest inertant concentration that did not produce an explosion for a given fuel concentration.

Table 4.4: Experimental test matrix.

Coal Dust Type	Vessel Type	Coal Dust Concentration [g/m ³]	Rock Dust Type	Ignition Energy [kJ]
CBDC Mine-Size	20-L	500	CBDC Regular Dolomite	1, 5, 10
CBDC Mine-Size	20-L	1000	CBDC Regular Dolomite	5
CBDC Mine-Size	1-m ³	500	CBDC Regular Dolomite	2.5, 5, 10, 30
CBDC Mine-Size	1-m ³	1000	CBDC Regular Dolomite	5, 10
CBDC Mine-Size	1-m ³	500	AlM Baghouse Limestone	10
Pittsburgh Pulverized	20-L	250 – 1000	NIOSH PRL Limestone	5
Pittsburgh Pulverized	1-m ³	250 – 2000	NIOSH PRL Limestone	10

4.4 RESULTS AND DISCUSSION

4.4.1 Mine-Size Coal Dust Inerting Results

To determine the influence of scale on the inerting level of mine-size coal dust, experiments were conducted using a fixed concentration of fuel dust, while varying the

relative concentration of dolomite. Some of the results in this section have been previously presented by Dastidar *et al.* (1998b) (subsequently appearing in print as Dastidar *et al.*, (1998c)). There are two reasons for including these results here – their relative importance to the remainder of the current work, and the extended analysis provided in this section.

The overpressure and rate of pressure rise of the explosions were determined from the recorded pressure time traces. Inertant was added to the mixture until the measured overpressure was below the 2 bar(a) explosion criterion. Figure 4.3 is a plot of explosion overpressure (P_m) as a function of rock dust concentration for a fuel concentration of 500 g/m³ and an ignition energy of 2.5 kJ in the 1-m³ chamber. The inerting level is the rock dust concentration at which this curve crosses the 2 bar(a) explosion criterion, as shown in Figure 4.3.

In the 1-m³ chamber, the inerting level was determined using ignition energies of 2.5, 5, 10, and 30 kJ, for 500 g/m³ of coal dust. Ignition energies of 5 and 10 kJ were used for 1000 g/m³ of fuel. In the 20-L chamber, tests were conducted with 1, 5, and 10 kJ, for 500 g/m³ of fuel. An ignition energy of 5 kJ was used for 1000 g/m³ of fuel. The ignition energies were selected to provide a range of ignition strengths in each vessel. It should be noted that when conducting standard explosibility tests such as for P_{max} and K_{St} in these chambers, standard procedures (e.g. ASTM or ISO) call for an ignition strength of 10 kJ in both the 1-m³ and 20-L chambers.

The preferred approach would have been to compare mine-size coal dust inerting work conducted in the 1-m³ chamber with that previously done in the 20-L chamber (Dastidar *et al.*, (1997)). Unfortunately, there was insufficient prepared material from the 20-L tests remaining for 1-m³ testing. Therefore, a new sample of coal was obtained from the CBDC. Proximate analysis of the sample indicated that the coal was unwashed and had a higher ash content of 27 %. (The previous sample used by Dastidar *et al.* (1997) had 3.7 % ash.)

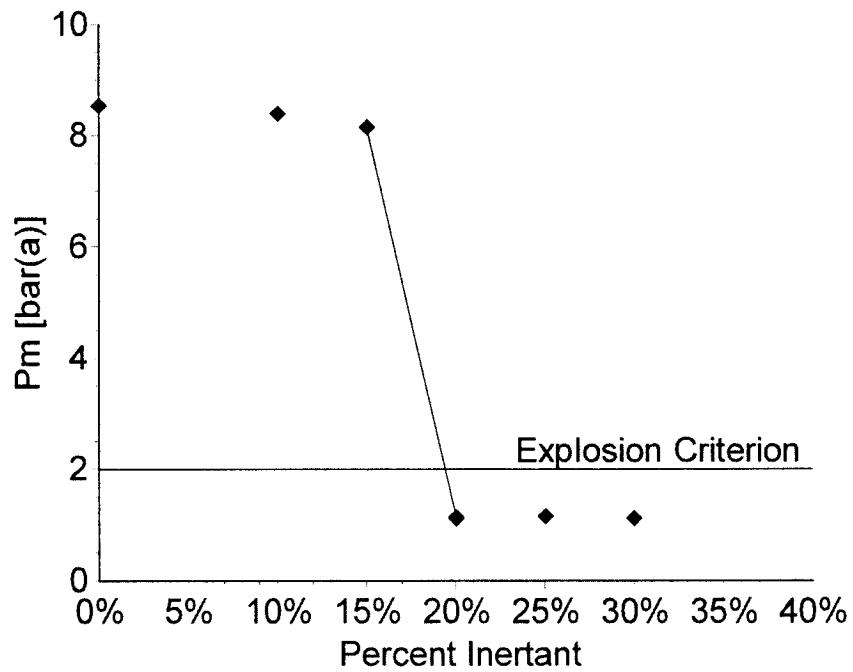


Figure 4.3: Inerting 500 g/m³ of mine-size coal dust in a 1-m³ chamber using a 2.5-kJ ignition source.

Inerting level testing was therefore performed on the new sample of coal in the 20-L Siwek chamber and compared to previously published results. Figure 4.4 gives this comparison in the form of a plot of total incombustible content (TIC: rock dust, coal moisture and coal ash) as a function of ignition energy. TIC was used to compensate for the differences in ash content of the two mine-size coal samples (previous work and current work). As can be seen, the inerting results for these different samples are similar when expressed in terms of TIC. Because of this similarity, the new coal sample was deemed suitable for testing in the 1-m³ chamber to facilitate comparison of laboratory-scale inerting levels with those determined in an intermediate-scale vessel.

Figure 4.5 compares the inerting level (expressed as % rock dust) of CBDC mine-size coal dust in the 1-m³ chamber to that measured in the 20-L Siwek chamber. The inerting levels determined in the 1-m³ chamber are lower than those observed in the 20-L chamber for all ignition energies. In the 1-m³ chamber there is a significant difference in the inerting level between a 2.5-kJ ignition source and a 5-kJ ignition source. However, there was little change in the inerting level as the ignition energy was increased further. A doubling of the ignition energy from 5 kJ to 10 kJ did not produce a significant increase in inerting level; both energies resulted in an inerting level of 34 % rock dust. A six-fold increase in ignition energy from 5 kJ to 30 kJ resulted in an increase of the inerting level from 34 % to 39 % rock dust. Tests were also conducted at a higher fuel concentration of 1000 g/m³ using 5- and 10-kJ ignition sources. In the 1-m³ chamber there was no change in the inerting level.

In the 20-L Siwek chamber there is a strong relationship between ignition energy and inerting level. Using a 1-kJ ignition source, the inerting level was determined to be 49 % rock dust; this increased to 67 % and 74 % for 5-kJ and 10-kJ sources, respectively. These observations are similar to those made by Cashdollar and Chatrathi (1992) for the dependence of the minimum explosible concentration (MEC) on ignition energy. The strength of the ignition source had a greater influence on the MEC in the 20-L chamber than in the 1-m³ chamber. The authors attributed the lower MEC's in the 20-L chamber to overdriving (as described later in this section).

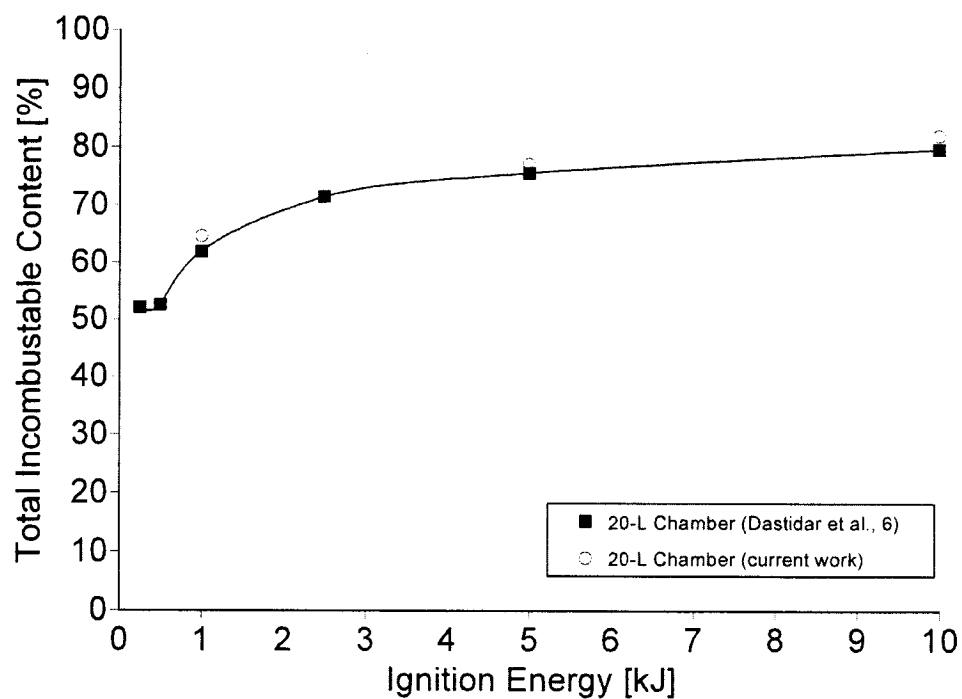


Figure 4.4: Percent total incombustible content required to inert as a function of ignition energy for mine-size coal dust (500 g/m³ coal dust concentration).

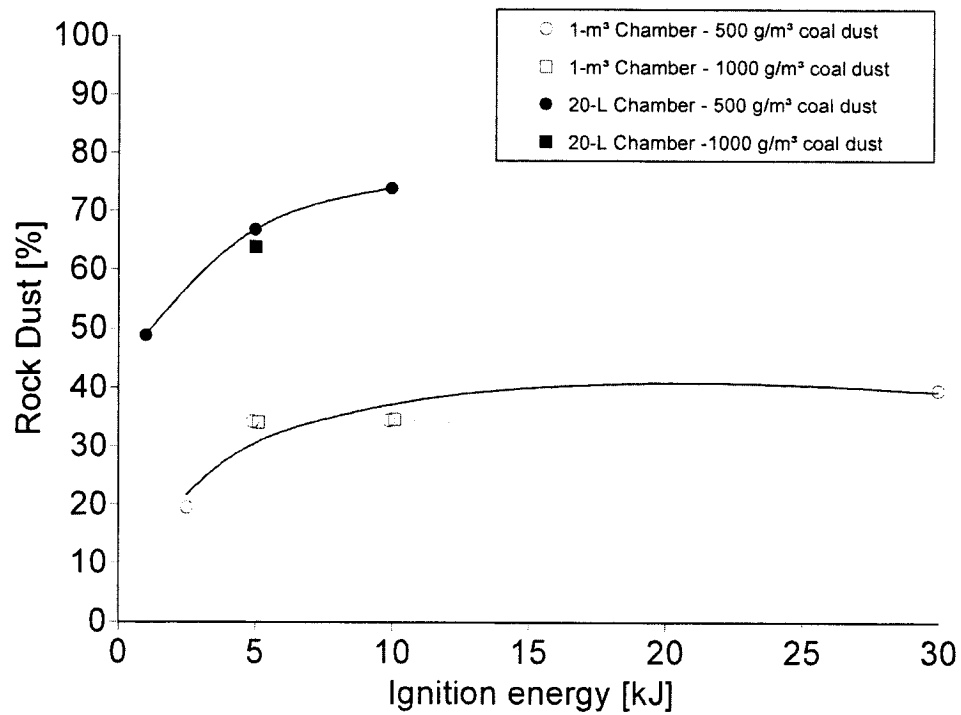


Figure 4.5: Percent rock dust required to inert as a function of ignition energy for mine-size coal dust in 1-m³ and 20-L chambers.

Siwek (1980) has previously demonstrated that inerting levels in a 20-L chamber determined with a 1-kJ ignition source agreed well with those measured in a 1-m³ chamber using a 10-kJ ignition source. The current results support this trend toward closer agreement between laboratory-scale and intermediate-scale inerting levels with a decrease in laboratory-scale ignition energy. As shown in Figure 4.5, however, the inerting level using a 1-kJ ignitor in the 20-L chamber (49 % rock dust) was still significantly higher than the inerting level found in the 1-m³ chamber using a 10 kJ ignition source (34 % rock dust).

These results also support the comments made by Zhen and Leuckel (1997); i.e. that the smaller 20-L chamber is affected by the chosen ignition energy to a greater extent than the 1-m³ chamber. According to these authors, a volumetric/multipoint ignition source such as a pyrotechnic ignitor has a limited effect on the explosion parameters in a 1-m³ vessel. Dust explosion experiments performed using 75-J and 10-kJ ignition sources produced nearly the same overpressure, but different rates of pressure rise for cornstarch (Zhen and Leuckel (1997)). The ignitor volume in a 1-m³ vessel may be considered to be relatively small compared to the chamber volume; therefore there exists a reduced sensitivity of explosion overpressure to ignition energy. The authors comment, however, that in smaller chambers the volumetric/multipoint nature of the ignition source is of greater importance because it produces a relatively larger ignition kernel. (A 5-kJ ignitor can produce a flame that is about 35 % the size of a 20-L chamber). This large flame may have a stronger influence on the explosion parameters.

This greater influence is seen in the form of overdriving combustion in the 20-L chamber. Overdriving of the explosion occurs when the ignition source (and as a result the flame produced by the ignition source) is large compared to the vessel volume. This has two consequences. First, it changes the initial test conditions of the dust cloud (increasing the temperature), thereby possibly making a nonexplosible dust explosible. It can also result in burning of the dust within the ignitor flame, but with no real propagation beyond the ignition source. Since the ignition source volume is very large compared to the vessel volume, the dust appears to explode and as a result the overpressure and rate of pressure rise are overestimated.

As an example of the overdriving phenomenon, one may consider the work of Cashdollar and Chatrathi (1992) and Cashdollar *et al.* (1992), which has shown that anthracite tested in a 20-L chamber using a 5-kJ ignition source was explosible. However, in a 1-m³ vessel even a very strong 30-kJ ignition source did not produce an explosion.

These authors also determined the minimum explosible concentration (MEC) for Pittsburgh coal (37 % volatile matter) and gilsonite (84 % volatile matter) at different ignition energies. The 20-L chamber showed evidence of overdriving because it produced MEC levels lower than the 1-m³ chamber. An interesting observation from this work (Cashdollar and Chatrathi (1992), Cashdollar *et al.*, (1992)) is that the MEC of gilsonite did not change as significantly as the MEC of Pittsburgh coal, as ignition energy was increased. This was possibly due to the higher volatile content of gilsonite. Sufficient volatile matter may have been released from the gilsonite quickly enough to produce a flammable mixture of fuel and air to take part in the combustion process before the flame front was quenched by the wall. For Pittsburgh coal, the higher ignition energies were able to release greater amounts of volatile matter from the dust. This volatile matter was present in sufficient quantity to form flammable concentrations from smaller quantities of dust, leading to lower MEC's.

More recent work by Going *et al.* (2000) has shown that in addition to the decrease in the MEC in 20-L chamber tests due to a strong ignition source, a decrease in the limiting oxygen concentration (LOC) of dusts has also been observed. The authors report that low ignition energies in the 20-L chamber are required to obtain LOC's similar to those measured in a 1-m³ chamber using a 10-kJ ignitor. For Pittsburgh pulverized coal dust, the LOC in the 1-m³ chamber (10-kJ ignition energy) was between 13 and 14 % oxygen. In the 20-L chamber, however, an ignition energy of 1 kJ was required to give similar results. This finding supports the results presented in the current paper for inerting coal dust with a solid inertant (given that the LOC of coal dust can similarly be interpreted as an inerting process, albeit with the gaseous inertant, nitrogen).

The inerting level, the LOC and the MEC all represent limit flame conditions. In the case of the inerting level, the solid matter used to prevent an explosion acts as a thermal sink,

absorbing heat from the ignition source preventing the ignition of the fuel dust. The solid matter also acts as a diluent, reducing the concentration of fuel exposed to the transient ignition source (pyrotechnic ignitor). In addition, the added matter increases the dust cloud density and may inhibit oxygen migration to the flame front.

As previously mentioned, the LOC is similar to the inerting level, although the LOC involves inerting with a gaseous rather than solid material. The nitrogen which replaces the oxygen in LOC experiments, acts as a thermal sink, cooling the flame and preventing flame propagation. Additionally, the diluting effect of the increased nitrogen concentration starves the combustion reaction of oxygen. Similarly, the MEC is a limit flame condition in which there is insufficient fuel to sustain combustion. The heat losses to the surrounding gases prevent ignition of neighboring fuel particles, thereby inhibiting flame propagation. The overdriving phenomenon observed in the 20-L chamber for MEC and LOC determination is also clearly present for inerting level determination in this smaller volume.

4.4.2 *Influence of Rock Dust Particle Size*

Previous work in laboratory-scale chambers (Dastidar *et al.* (1997), Cashdollar and Hertzberg (1989), Amyotte *et al.* (1995)) has shown that less rock dust is required to prevent a coal dust explosion as the inertant particle size is decreased. To test the influence of scale on these results, additional experiments were performed in the 1-m³ chamber using mine-size coal dust and waste baghouse limestone from AIM. As in the case of the mine-size coal dust, there was insufficient baghouse limestone remaining from our previous 20-L work (Dastidar *et al.* (1997)) to conduct inerting tests in the 1-m³ vessel. A new sample of limestone was therefore obtained from AIM.

The mean particle diameter of the AIM baghouse material from our previous work (Dastidar *et al.* (1997)) was 12 μm ; the new material had a mean diameter of 26 μm . Even though this new material was larger than the baghouse limestone used by Dastidar *et al.* (1997), it was smaller than the rock dust obtained from the CBDC ($D_w = 50 \mu\text{m}$). The influence of rock dust particle size on the inerting level could therefore still be examined.

Experiments were performed in the 1-m³ chamber using a 10-kJ ignition source and 500 g/m³ of CBDC mine-size coal dust as the fuel. Figure 4.6 is a plot of explosion overpressure as a function of rock dust concentration for, in the 1-m³ chamber, AIM baghouse limestone and CBDC regular dolomite. Results from previous 20-L experiments conducted at similar fuel dust conditions (Dastidar *et al.* (1997)) have also been included. In this previous work, the inerting level using AIM baghouse limestone ($D_w = 12 \mu\text{m}$) was 64 %. When AIM regular limestone ($D_w = 31 \mu\text{m}$) was used, the inerting level was 69 %; CBDC regular dolomite ($D_w = 65 \mu\text{m}$) required 74 % rock dust to prevent an explosion.

The current experiments conducted in the 1-m³ chamber show a similar dependence of the inerting level on the particle size of the rock dust used. From Figure 4.6, the inerting level in the 1-m³ chamber using CBDC regular dolomite ($D_w = 50 \mu\text{m}$) was 34 % (as reported previously in this paper). The inerting level using the AIM baghouse limestone ($D_w = 26 \mu\text{m}$) was 23 %. A decrease in the particle size of the inertant results in a decrease in the amount of inertant required to prevent an explosion. This phenomenon is due, in part, to the increase in rock dust surface area that accompanies a reduction in rock dust particle size. This promotes greater radiant heat absorption and subsequent flame quenching.

Recalling Figure 4.4, a comparison of inerting levels on the basis of explosion chamber volume must be made in terms of total incombustible content (TIC). When expressed in this manner, the 1-m³ results become 54 % TIC and 46 % TIC for CBDC regular dolomite and AIM baghouse limestone, respectively (for a relative decrease of 15 %). The most appropriate materials for comparison (with respect to rock dust particle size) from the previous 20-L testing (Dastidar *et al.* (1997)) are CBDC regular dolomite and AIM regular limestone, for which the inerting levels are 75 % TIC and 71 % TIC, respectively. Here the relative decrease in inerting levels is 5 %. When expressed on a mass per unit volume basis, however, the percentage reduction in total incombustible

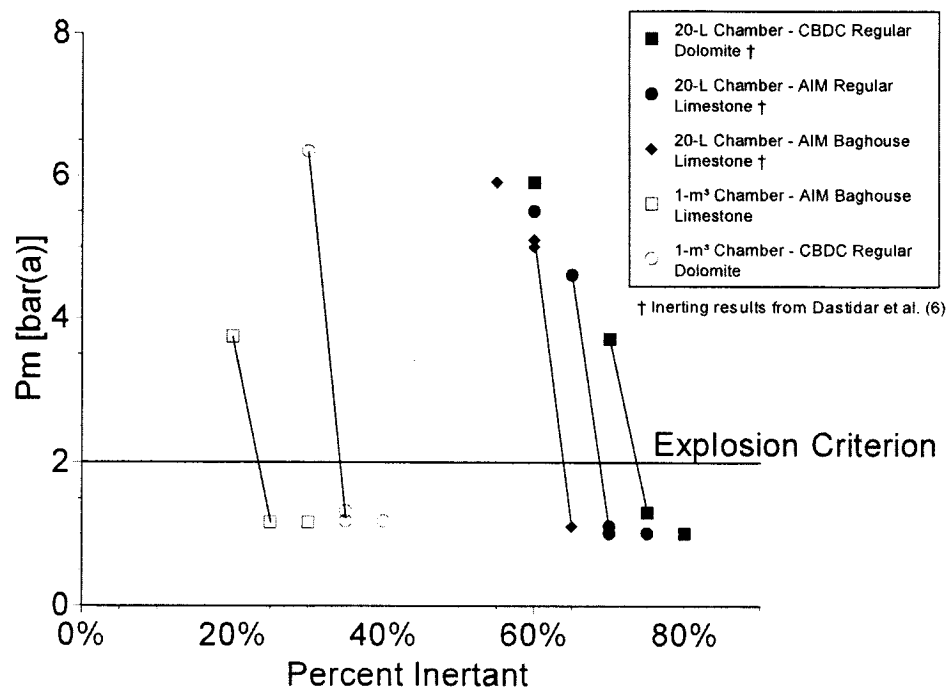


Figure 4.6: Inerting of mine-size coal dust in 1-m³ and 20-L chambers.

matter content is similar for both chambers. There is a 27 % decrease in TIC in the 1-m³ chamber (from 410 g/m³ to 301 g/m³), and a 21 % decrease in TIC in the 20-L chamber (from 1449 g/m³ to 1138 g/m³).

Nagy (1981) reports that particle size of the limestone also affects the inerting level of coal dust explosions in mine-scale experiments. As the particle size of the limestone inertant is decreased the TIC required to inert the fuel dust also decreases.

These results provide definitive evidence of the reduction in inerting level achievable when finer sized inertants are used. The current work has clearly demonstrated this point on a scale that more closely approaches typical industrial plant than the previously used 20-L chamber. Although additional testing on a true industrial scale would be prudent, there are several implications arising from the current and previous work (Dastidar *et al.* (1997)). There are issues of economics relating to industrial supplies of fine-sized rock dust, sustainability with respect to production of baghouse material and waste reduction, and regulatory matters concerning rock dust requirements in coal mines.

4.4.3 *Pulverized Coal Dust Inerting Results*

To facilitate the comparison of coal dust inerting levels among laboratory-scale, intermediate-scale and mine-scale work, it is best to use the same type of coal and rock dust in all tests. Inerting experiments using CBDC coal dust have not, however, been conducted in mine-scale geometries. This poses a limitation in comparing inerting levels determined in the 20-L and 1-m³ chambers to those observed in mine-scale experiments. In our previous work (Dastidar *et al.* (1997)), Pittsburgh and Pocahontas pulverized coal dusts were used along with NIOSH limestone. This allowed comparison of our results in the 20-L Siwek chamber with the NIOSH LLEM and the NIOSH 20-L test chamber. Pittsburgh pulverized coal dust and NIOSH limestone have therefore been used for 1-m³ inerting level determination in the current work so as to allow comparison with previous inerting results.

Dependence of the NIOSH PRL limestone inerting level on the concentration of Pittsburgh pulverized coal dust used for experimentation was observed in earlier 20-L

work (Dastidar *et al.* (1997)). This dependence has also been observed in the 1-m³ test volume. Figure 4.7 shows a plot of explosion overpressure as a function of coal dust concentration for varying amounts of limestone. The experiments were conducted in the 1-m³ chamber using a 10-kJ ignitor. Coal dust concentration was varied from 250 to 2000 g/m³ in increments of 250 g/m³.

The results confirm the concentration dependence observed in previous work. Lower concentrations of fuel (250 – 750 g/m³) required greater amounts of limestone to prevent an explosion than higher concentrations of fuel dust. From Figure 4.7, a coal dust concentration of 250 g/m³ required a mixture concentration of 53 % rock dust to prevent an explosion, whereas for a coal dust concentration of 2000 g/m³, only 28 % rock dust in the mixture was required. The highest inerting level was observed at 500 g/m³ where 59 % rock dust was required to prevent an explosion.

Previous work could not be used for comparison to these 1-m³ chamber results because only limited rock dust concentrations (75 and 80 %) were tested by Dastidar *et al.* (1997). As a result the inerting level at higher coal dust concentrations could only be reported as less than 75 %. The current work tested a larger range of rock dust concentrations so as to determine the actual inerting level.

Inerting experiments using Pittsburgh pulverized coal dust were performed in the 20-L test chamber using a 5-kJ ignition source. This ignitor strength was selected because it produced inerting levels similar to those observed in the LLEM (Dastidar *et al.*, (1997)). Coal dust concentration was varied from 250 to 1000 g/m³, again in increments of 250 g/m³. Higher coal dust concentrations could not be tested due to dust dispersion limitations; high dust loadings may not produce the evenly dispersed dust cloud that is required for testing.

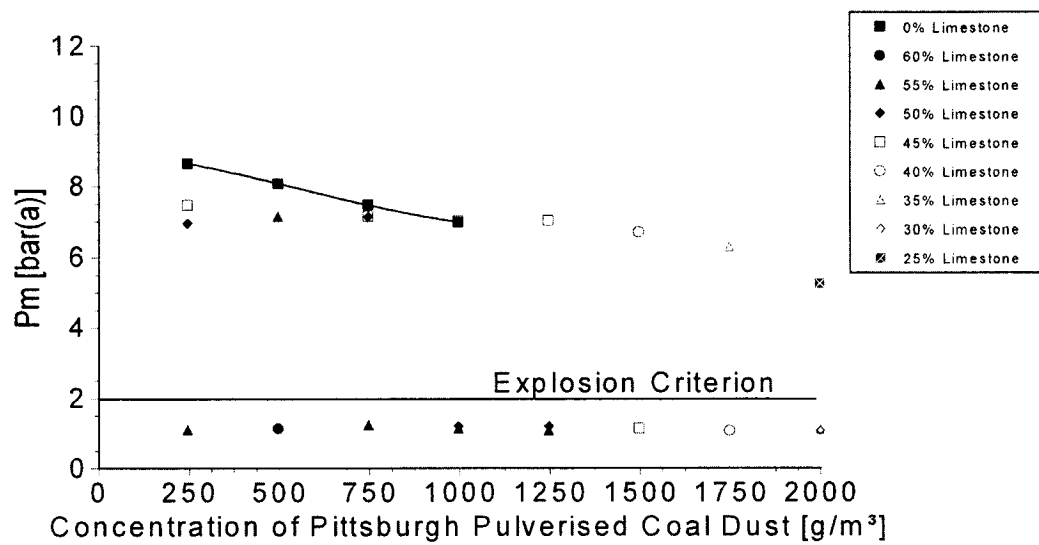


Figure 4.7: Overpressure as a function of Pittsburgh pulverized coal concentration in a 1-m³ chamber for varying amounts of rock dust using a 10-kJ ignition source.

Figure 4.8 shows a plot of the explosion overpressure in the 20-L chamber as a function of coal dust concentration for varying amounts of rock dust. The inerting level dependence on coal concentration is also apparent in these experiments. Lower concentrations of coal dust require more rock dust to prevent an explosion. For example, a coal dust concentration of 250 g/m³ required 73 % rock dust in the total mixture to prevent an explosion, while a coal dust concentration of 1000 g/m³ required 69 % rock dust. Also, as in the 1-m³ vessel, the highest inerting level observed in the 20-L chamber was at a concentration of 500 g/m³ of coal dust where 74 % rock dust was required to prevent an explosion.

These results for Pittsburgh pulverized coal in the 20-L chamber are slightly lower than previously reported (Dastidar *et al.* (1997)). In Dastidar *et al.* (1997), inerting 200 g/m³ of Pittsburgh pulverized coal dust required 78 % NIOSH limestone and 300 g/m³ of coal dust required 77 % limestone. The differences between the current results and the previous work may be due to the nature of flame propagation, which is probabilistic at limit conditions. For example, when testing 300 g/m³ of coal dust with 75 % limestone (Dastidar *et al.* (1997)), three repeat tests were performed; of those three tests, two resulted in an explosion.

Figure 4.9 compares the inerting levels for Pittsburgh pulverized coal dust determined in the 20-L and 1-m³ chambers by plotting percent rock dust required to prevent a dust explosion against the concentration of fuel in the mixture. The results show that the inerting levels in the 1-m³ chamber are lower than those determined in the 20-L vessel; the 1-m³ chamber requires less rock dust to prevent an explosion than the 20-L chamber for all coal dust concentrations tested. This is similar to the results from the CBDC mine-size coal dust inerting discussed earlier. The inerting level for Pittsburgh pulverized coal in mine-scale experiments is 79 % rock dust when using a fuel concentration of 200 g/m³ (Sapko *et al.* (1989), Sapko *et al.* (2000)). In the 20-L chamber using a similar fuel concentration of 250 g/m³, the inerting level from the current work was 73 % rock dust. However, in both chambers 500 g/m³ of coal dust required the greatest amount of inertant to prevent an explosion.

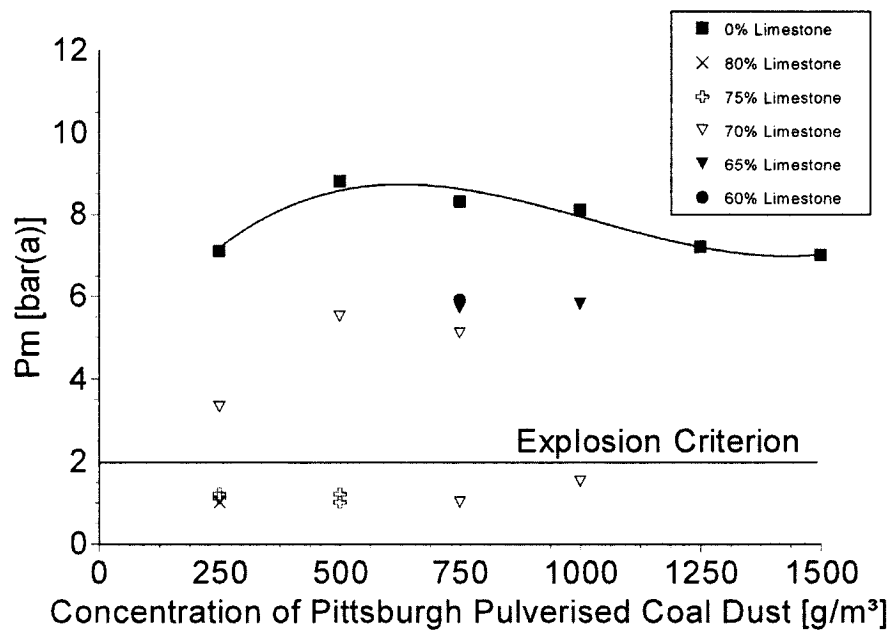


Figure 4.8: Overpressure as a function of Pittsburgh pulverized coal concentration in a 20-L chamber for varying amounts of rock dust using a 5-kJ ignition source.

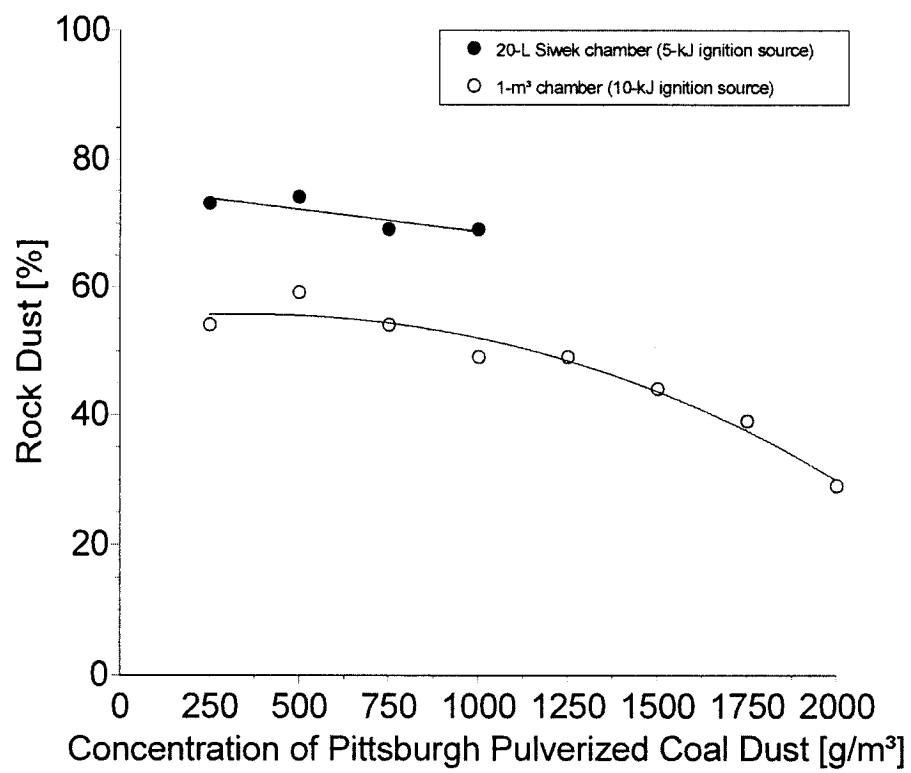


Figure 4.9: Inerting curves for Pittsburgh pulverized coal dust in 1-m³ and 20-L chambers.

The current work provides new insight to previous inerting level tests. The favorable comparison between NIOSH PRL LLEM inerting levels and those determined in the 20-L Siwek chamber (which prompted the current study), may have been somewhat coincidental. The strong ignition energy used in the 20-L volume may have overdriven the chamber, resulting in a high inerting level. Inerting levels determined in the LLEM may be greatly affected by flame acceleration and pressure piling in the long mine gallery (leading to an increase in the amount of inertant required to prevent an explosion). Roughly, the small-chamber overdriving may equate to increased burning due to flame acceleration in the mine.

From a modeling perspective, Sapko *et al.* (2000) reported good agreement between NIOSH LLEM and NIOSH 20-L inerting results with a thermodynamic model which was developed to estimate the amount of limestone required to inert a coal dust explosion. As expected in light of the current work, the inerting levels from this model are greater than those determined in the 1-m³ chamber. The reason for this difference may be a model assumption that the volatile content of the coal dust is 50 %. This value is greater than that determined by standard proximate analysis (36 %).

The relatively large volumetric ignition source in the 20-L chamber and the thick flame zone in mine-scale explosions may liberate more volatile material from the coal dust than that determined by proximate analysis. It is known that as ignition source strength increases in the 20-L test chamber, MEC and inerting level results for Pittsburgh (36 % volatile matter) and Pocahontas (16 % volatile matter) pulverized coal dusts become similar (Chawla *et al.* (1996)). This may be attributed to the liberation of greater amounts of volatile material from the coal dust at higher ignition energies. On the other hand, the relatively more localized ignition source in the 1-m³ chamber may not liberate as much volatile material. Thus, less inert matter is needed to prevent an explosion. It therefore stands to reason that use of lower volatile matter content in the NIOSH inerting model (Sapko *et al.* (2000)) may result in agreement between the 1-m³ chamber inerting levels and those determined by the model.

It must be remembered however, that mine-scale experiments, and the modeling of such experiments, replicate a specific industrial scenario. Inerting levels determined in the LLEM are therefore entirely representative of explosion suppression requirements in that scenario. Attempts to match those inerting levels through manipulation of test variables (e.g. ignition energy) in 20-L testing, are attempts to replicate the full-scale mine scenario. The fact that flame acceleration and overdriving may be involved in the physics of mine-scale and laboratory-scale testing, respectively, becomes somewhat irrelevant.

On this point, it should be noted that ignition energy does not influence the determination of the peak overpressure as greatly where there is a significant level of combustion. The energy released from the burning dust cloud is significantly greater than that of the ignition source. This can be seen by the similarity in overpressure measurements determined in chambers having different volumes.

However, in limit conditions such as the MEC, LOC and inerting level determination, the energy-to-volume ratio of the ignition source plays an important role. This may imply that test conditions in the 20-L chamber should be varied according to the type of process hazard being examined. It is possible that stronger ignition sources should be used when results are to be extrapolated to mine galleries or silos (geometries with high L/D ratios), and weaker ignition sources used when comparing the smaller vessel results to those from intermediate-scale vessels (or geometries with low L/D ratios).

4.5 CONCLUSION

The inerting level for coal dust mixed with rock dust has been determined in the 1-m³ chamber and compared to inerting levels determined in the 20-L Siwek chamber. The 1-m³ inerting levels were lower than those found in the 20-L chamber for both mine-size coal and pulverized coal dust. This may be caused by too strong an ignition energy overdriving the smaller chamber. Agreement between the 20-L chamber (using a 5-kJ ignition source) and mine-scale inerting levels may be due to overdriving of the smaller chamber reproducing the effects of flame acceleration on mine-scale results. It is possible that test conditions for inerting level determination have to be modified depending on the scale to which the results will be extrapolated. This may imply the use of relatively weak

ignition sources for geometries with low L/D ratios and high ignition energies for geometries with high L/D ratios.

Reduction in the particle size of the rock dust used for inerting has been found to influence the quantity required to prevent an explosion in the 1-m³ chamber. This agrees with work conducted in smaller chambers.

4.6 ACKNOWLEDGMENTS

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5 A CALCULATED ADIABATIC FLAME TEMPERATURE MODEL FOR THE PREDICTION OF DUST EXPLOSION INERTING LEVELS

This section was originally published as:

A. Dastidar and P. Amyotte, "*Using calculated adiabatic flame temperatures to determine dust explosion inerting requirements*", **Trans IChemE, Process Safety and Environmental Protection**, vol. 82, Part B, pp. 142-155, 2004*. The text and figures in this section are identical to that of the published paper with the exception that section numbers have been added, and figure and table numbers have been changed, to reflect the thesis format.

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5.1 ABSTRACT

The use of calculated adiabatic flame temperatures (CAFT), along with a selected limit flame temperature for combustion propagation, has been shown to be effective in determining the flammability envelope for hydrocarbon gases (Melhem, 1997 and Mashuga and Crowl, 1999). This paper discusses the use of this methodology to determine the flammability of gaseous fuel/oxidizer/inertant mixtures.

The paper then proceeds to describe how this methodology can be modified into a predictive tool to determine the flammability of a solid fuel/inertant mixture in air. The modification proposed here is based upon previous work by Hertzberg *et al.* (1984, 1986). Their model proposes that in the homogeneous mechanism for combustion (which is predominant for most carbonaceous fuels and some metal dusts) not all the volatile matter present in the system can participate in the combustion process. Only a fraction (termed the beta fraction) can be devolatilized rapidly enough to take part in combustion. It is this fraction of fuel that is used for the adiabatic flame temperature calculations.

The model presented here differs from Hertzberg *et al.* (1984, 1986) in that it has been modified to allow for comparisons between inerting levels determined in a 20-L chamber and a 1-m³ chamber. The results indicate that the 1-m³ model can be used to predict the experimental inerting levels of the 1-m³ chamber, with limitations. Additionally, the 20-L CAFT model can be used to predict the experimental inerting levels in the 1-m³ chamber (again, with limitations). Ultimately, the utility of this modified model as a predictive tool for inerting level and minimum inerting concentration determination has been demonstrated.

5.2 INTRODUCTION

Explosions are gas-dynamic phenomena characterized by rapid increases in pressure that generate destructive forces. They are a serious hazard in the chemical process industries since these destructive forces can destroy plant equipment and cause injury to personnel.

One of the ways to mitigate the effects of an explosion is by inerting: the addition of a third compound that does not take part in the combustion process. This inert compound acts as a diluting agent and also as a heat sink, thereby preventing flame propagation. In some cases, the inerting material may act chemically, preventing flame propagation by capturing free radicals and inhibiting the kinetic combustion mechanism. One of the most common forms of gaseous inertant used in industry for carbon-based fuels is nitrogen. Monoammonium phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$) and sodium bicarbonate (NaHCO_3) are two of the most common solid inertants used to suppress dust explosions.

Explosibility testing must be performed to determine the amount of inertant required to prevent an explosion. Ideally, these tests should be performed at the scale of the operating environment where the hazard exists. However, the size and number of the experiments required for adequate inerting level determination can make this expensive and possibly hazardous. As a result, these tests are usually performed on a smaller scale. The most common types of these smaller testing equipment are the “laboratory-scale” 20-L chamber and the “intermediate-scale” 1-m³ chamber.

Good agreement between coal dust inerting levels determined in the 20-L Siwek chamber with mine-scale results (Dastidar *et al.*, 1997) has prompted interest in comparing laboratory-scale inerting levels with those determined in an intermediate-scale chamber. The intermediate-scale chamber has been used to determine the amount of monoammonium phosphate, sodium bicarbonate and limestone required to prevent explosions of aluminum, anthraquinone, polyethylene, cornstarch and Pittsburgh pulverized coal dust (Dastidar *et al.*, 1998c, 1999 and Dastidar and Amyotte, 2002). The objective of this work was to determine if inerting levels of these fuel/inertant mixtures in the 20-L chamber were comparable to those found in the 1-m³ chamber. Good agreement between the inerting levels determined in the 20-L and the 1-m³ chamber was found to

occur when low energy ignition sources were used for experiments in the 20-L chamber (Dastidar and Amyotte, 2002).

A large number of flammability tests need to be performed to determine the amount of inert matter required to prevent flame propagation. The use of computer-aided flame temperature calculations can help minimize the number of experiments that need to be conducted. The calculated adiabatic flame temperature at constant pressure, along with a set minimum flame propagation temperature, can be used to differentiate the fuel/oxidant/inert mixtures that are combustible from those that are not.

The current work demonstrates the use of calculated adiabatic flame temperatures as a predictive tool to estimate the inerting requirements for dust explosions using solid inertants. Additionally, this paper uses the CAFT model to explain the differences in inerting levels observed between the 1-m³ chamber and the 20-L Siwek chamber.

5.3 CALCULATED ADIABATIC FLAME TEMPERATURE MODEL FOR GASEOUS FUELS

The use of calculated adiabatic flame temperatures, along with a selected limit flame temperature for combustion propagation, has been shown to be effective in determining the flammability envelope for hydrocarbon gases (Melhem, 1997 and Mashuga and Crowl, 1999).

There are five steps involved in determining the flammability envelope using an adiabatic flame temperature model for a homogeneous combustion mechanism (where both the fuel and oxidant are in the gaseous state): selection of the desired reactants, selection of the test condition, selection of the limit flame temperature, modification of the reactants, and construction of a flammability envelope from calculations.

5.3.1 Selection of Desired Reactants

In this first step, a decision must be made as to the reactant species that will be present in the system and the quantities of each. In many cases the computer programs used for the calculations have a list of reactant and product species. If any of the data for the species

to be studied are not found in the program, they may be obtained from other sources such as the JANAF tables or from the internet (F*A*C*T Thermochemical Database, 2000 and NIST Chemistry WebBook, 2000).

5.3.2 Selection of Test Condition

The next step is to decide whether the combustion process is taking place in an open system where the pressure remains constant or in a closed system where the pressure increases due to combustion. The selection of the system type (open or closed) will depend upon whether the model will be compared to open or closed system experimental data.

5.3.3 Selection of the Limit Flame Temperature

The limit flame temperature for combustion can be either selected based on theoretical principles or determined experimentally. Each method has its own limitations.

From previous work, the limit flame temperatures of hydrocarbons fall in the range of 1000 K to 1500 K (Coward and Jones, 1952). This is a large range, and thus poses a problem. If a high value is selected for the limit flame temperature then it is possible that the model may fail to predict flame propagation in a reactant mixture that has been shown to explode under experimental conditions. At the other extreme, selection of a low limit flame temperature, e.g. 1000 K, creates the situation where the model may predict an explosion where experimental results show none to occur. Some researchers select the lower value for the limit flame temperature, thereby making a conservative/safer flammability hazard prediction.

Others select a midrange temperature. While this selection may look like a compromise between the extreme temperature limits, it has a basis in theory. The reaction of carbon monoxide to carbon dioxide is highly exothermic and constitutes a significant proportion of the flame energy (Glassman, 1977). This reaction does not become significant until 1100 K, and at 1400 K it becomes self-sustaining. For this reason Mashuga and Crowl (1999) selected a value of 1200 K for the limit flame temperature.

In the second method of selecting the limit flame temperature, actual experimental results are used. Here, the flammability limit is determined experimentally for the fuel mixed in air, and the adiabatic flame temperature is determined for this mixture. This flame temperature is then used as the limit flame temperature for this fuel for all ratios of fuel/oxidant/inertant. There are two limitations of this methodology; first, experiments must be performed before the flammability hazard can be evaluated and second, the flammability limit depends upon the experimental procedure and apparatus. The type of test vessel and propagation criterion used as well as ignition source strength affect the measurement of the flammability limit (Britton, 2002).

Ideally, it would be beneficial to use existing data for lower flammability limits for the fuel. However, if the fuel is a compound for which no data on the lower flammable limit exist, then the data have to be determined experimentally. This may require extensive testing.

5.3.4 Modification of Reactants and Construction of a Flammability Envelope from Calculations

Once the limit flame temperature has been decided upon, model calculations are performed on the given reactant mixture (species concentrations) and the adiabatic flame temperature is determined. Flame propagation is considered to have occurred only if the temperature is greater than the limit flame temperature. The reactant mixture composition is then modified to create data sets for propagation and non-propagation mixtures.

This type of model shows good agreement with the experimentally determined flammability limits. Regions outside the derived envelope are nonflammable and regions within it are flammable. The shape of the envelope forms a nose. The nose of the envelope is related to the limiting oxygen concentration (LOC) for gaseous fuels but can also be interpreted as the minimum inerting concentration (MIC). Concentrations of the inertant above the MIC will prevent combustion regardless of fuel concentration.

5.4 CALCULATED ADIABATIC FLAME TEMPERATURE MODEL FOR DUSTS

The CAFT model cannot be directly applied to the inerting of dust explosions. When considering a gaseous system, the fuel is readily available to the oxidant and combustion can proceed by molecular collisions between the two species. The situation becomes complicated when the model is applied to a heterogeneous system with a solid fuel and gaseous oxidant. Such systems can undergo combustion by either heterogeneous or homogeneous combustion. The heterogeneous combustion mechanism involves a reaction between the solid fuel and gaseous oxidant on the surface of the dust particle. The homogeneous combustion mechanism requires a multi-step process where volatile material is expelled from the solid particle and mixed with the gaseous oxidant. Then this gaseous mixture of fuel and oxidant undergoes an exothermic reaction.

For many carbon-based dusts, and some metals, the homogeneous mechanism of combustion is thought to be more predominant than the heterogeneous mechanism. However, the computer programs that are used to calculate adiabatic flame temperatures and equilibrium composition assume that the reaction has an infinite amount of time to occur. They do not take into consideration kinetic factors involved in either surface oxidation reactions or devolatilization of a solid particle.

The flammability of the condensed fuel is dependent on several factors (e.g. particle size distribution, moisture content, impurities, etc.). An additional level of complexity occurs when the inert matter used is a solid and not a gas. Some research has been done in the use of calculated adiabatic flame temperatures to estimate inerting requirements for dust explosion inerting (Hertzberg *et al.*, 1984, 1986).

The model proposed by Hertzberg *et al.* (1984, 1986) uses an energy balance approach in which the fuel dust generates heat and the inert matter absorbs it. However, these authors assert that given the limited time scale of the explosion, only the volatile component of the fuel is able to undergo combustion and that the "solid" material remains inert and acts as a heat sink. They further claim (Hertzberg *et al.*, 1984, 1986) that because the flame temperature calculations assume that the system has an infinite time horizon; an

adjustment factor is needed to compensate for the temporary flame front. Their solution was to incorporate a “ β -Factor”, which is the fraction of the fuel that has time to participate in the transient combustion process. The authors modeled the combustion of coal dust at concentrations less than 600 g/m³ and used a calculated value of the β -Factor so that calculated explosion pressures matched explosion pressures observed in a 20-L chamber.

The objective of the current model is to adapt this previous methodology so that it can be used as a predictive tool to construct the inerting envelope for various solid fuel dust/inertant mixtures in air. The end user can use standard dust explosion characteristics test data such as explosion overpressure and minimum explosible concentration from ASTM E 1226 and ASTM E 1515, respectively, in conjunction with the model to estimate inerting levels. Additionally, the model is used to address the influence of scale on the inerting of dust explosions (Dastidar *et al.*, 1998c, 1999 and Dastidar and Amyotte, 2002) by adjusting the calculated explosion overpressures (β -Factor) to both 20-L and 1-m³ experimental results.

The CAFT model, used in conjunction with experimentally determined explosibility data (explosion pressure, rate of pressure rise and minimum explosible concentration), can then be used as a predictive tool to estimate the amount of inertant required to prevent an explosion. This approach has the potential of reducing the number of tests required to construct an inerting envelope.

5.5 CURRENT MODEL

The procedure to develop an inerting envelope for a heterogeneous system (solid fuel and inertant with a gaseous oxidant) is similar to that for a homogeneous gaseous system as described previously. The same five steps involved in determining the flammability envelope for gases using an adiabatic flame temperature model can also be used for dust clouds.

5.5.1 *Selection of Desired Reactants*

The fuels and inerting agents selected were those used in our previous experimental work (Dastidar and Amyotte, 2002 – in which the particle size distributions for these materials can be found): aluminum, anthraquinone, polyethylene, cornstarch and Pittsburgh pulverized coal dust as fuels, and sodium bicarbonate, monoammonium phosphate and limestone as inertants. Air was used as the oxidizer. The computer program used for calculating the adiabatic flame temperature was the NASA Lewis Code CEA 400 from the Lewis Research Center (Gordon and McBride, 1994, 1996).

When executed, the program calls for an input file that contains information about the system to be studied. The input must include the reactant species (fuel, inertant and air) and their respective molar concentrations. The initial temperature of each species must also be declared. The species must also be categorized as either “fuel” or “oxidizer”.

The input file must specify that the reaction is to be treated as an assigned enthalpy problem with a constant pressure of 1 bar and that the equilibrium products of the reaction should be listed in the output file. Although the computer program will automatically determine the appropriate equilibrium species that will minimize the Gibbs free energy of the system, it is sometimes necessary to force it to consider the inclusion of certain species (thereby assisting the program to converge to a solution).

To minimize computational load, equilibrium species having mole fractions below 1×10^{-7} were omitted from the output file. (This also reduces the size of the output file.) The output file contains a restatement of the input file followed by the various thermodynamic properties of the reacted system at chemical equilibrium. The most important properties considered in the inerting model are pressure and temperature. The output files conclude by listing the species making up the mixture and their respective mole fractions.

5.5.2 *Acquiring Thermochemical Data for Fuel Reactants*

The thermochemical data for each species that is to be used as a reactant or equilibrium product must be in the materials database of the CEA 400 program. However, many of the chemical species used for the inerting experiments (Dastidar and Amyotte, 2002)

were not present in the database. Thermochemical information for aluminum, polyethylene, limestone, and air were in the database, but thermochemical data were not available for anthraquinone, cornstarch, coal dust, sodium bicarbonate and monoammonium phosphate. As a result, the thermochemical data for these materials were obtained from the literature.

The required information for each chemical species consists of the molecular weight, molecular formula, C_p , H° , S° data, and heat of formation. For some fuel species (anthraquinone and cornstarch) only the heat of formation was found; the species may still be used in the program, however. The thermochemical information in the database for condensed phase hydrocarbon fuels (polyethylene(s), propane(l) and n-butane(l)) contain only molecular weight, molecular formula and heat of formation data. The heat of formation for anthraquinone was obtained from Ribeiro Da Silva *et al.* (1989) and Hildebrand *et al.* (1917). The heat of formation of cornstarch could not be found; however, the heat of formation of cellulose was obtained from Moore (1980). Cellulose and starch are organic polymers of glucose. They both have the same formula unit ($C_6H_{10}O_5$) but a different level of polymeric cross-linking (Starr and Taggart, 1987). The stoichiometry is therefore nearly the same between cellulose and starch, and the heats of formation are similar. Thus, the heat of formation of cellulose was used as an estimate for the unknown heat of formation of cornstarch.

Coal dust is a complex mixture of organic compounds. It is comprised of moisture, incombustible ash, fixed carbon and volatile material. When considering a homogeneous combustion mechanism for the combustion of coal dust in a dust explosion, only the volatile material takes part in combustion. The fixed carbon and ash both act as thermal heat sinks and do not contribute to the combustion process (Hertzberg *et al.* 1984, 1986). For the purposes of the model, the carbon and ash quantities (present in small amounts in washed coal) were combined, and a fictitious chemical element "char (s)" was created. It has the same thermochemical properties as carbon but is chemically inert like helium.

Hertzberg *et al.* (1986) also treated the fixed carbon in coal dust as an inert heat sink. Based upon chemical analysis of the volatile matter, the authors used the compositional

formula of $\text{CH}_{1.1}\text{O}_{0.06}\text{N}_{0.01}$ with a heat of formation of -8.4 kJ/mol. However, this may not be an appropriate composition for the model. The compositional formula may not be accurate since it depends upon the heat flux used to extract the tar volatiles from the coal and the test apparatus used for the analysis. In addition, the heat of formation used by Hertzberg *et al.* (1986) was an approximation. The true heat of formation of $\text{CH}_{1.1}\text{O}_{0.06}\text{N}_{0.01}$ is unknown. An alternative approach would be to use methane (CH_4) to represent the volatile matter. However, this leads to a higher concentration of hydrogen in the reaction mixture. Tar volatiles usually have a 1:1 ratio of C to H.

Another compositional approximation that can be used is benzene (C_6H_6) (Richmond *et al.* 1975, 1979). This has the correct ratio of carbon to hydrogen but is a liquid and not a solid at room temperature. Experiments by Cashdollar *et al.* (1988) have shown that a near 1:1 mixture of polyethylene dust and graphite dust has a minimum explosible concentration similar to Pittsburgh pulverized coal dust. Since both the inerting level and the minimum explosible concentration are limit flame conditions, it is possible to use polyethylene as a substitute for the volatile material. Polyethylene is a solid at room temperature and has a low carbon to hydrogen ratio. An added advantage is that the thermochemical data for polyethylene are available in the CEA 400 computer program database.

5.5.3 Acquiring Thermochemical Data for Inert Materials

Thermochemical information for sodium bicarbonate and monoammonium phosphate were not available in the program database. The thermochemical data for both these species were obtained from the F*A*C*T Thermochemical Database (2000) and NBS tables (Lide, 1982). The raw data of C_p , H° , S° as a function of temperature were fitted to equations 1 - 3 from Gordon and McBride (1994) to obtain the equation constants (a_1 , a_2 , a_3 , a_4 , a_5 , a_6 , a_7 , a_8 , a_9) for each species required in the CEA 400 program.

$$(1) \quad \frac{C_p^\circ}{R} = a_1 T^{-2} + a_2 T^{-1} + a_3 + a_4 T + a_5 T^2 + a_6 T^3 + a_7 T^4$$

$$(2) \quad \frac{H^\circ}{RT} = -a_1 T^{-2} + a_2 T^{-1} \ln T + a_3 + a_4 \frac{T}{2} + a_5 \frac{T^2}{3} + a_6 \frac{T^3}{4} + a_7 \frac{T^4}{5} + \frac{a_8}{T}$$

$$(3) \quad \frac{S^\circ}{R} = -a_1 \frac{T^{-2}}{2} - a_2 T^{-1} + a_3 \ln T + a_4 T + a_5 \frac{T^2}{2} + a_6 \frac{T^3}{3} + a_7 \frac{T^4}{4} + a_9$$

Since the CEA 400 computer program uses a nine-parameter equation to describe C_p , H° , and S° , the raw thermochemical data (as a function of temperature) were required. Other computer programs and literature sources that provide equation constants to fit thermodynamic parameters use seven constants in their equations. Thus, data from these cannot be used with the CEA 400 computer program.

The inertants sodium bicarbonate and monoammonium phosphate used in these experiments were modeled for three different conditions: chemically inert (i.e. no decomposition), degree of decomposition of the inertant determined by the CEA 400 computer algorithm, and intentionally decomposed fully. Comparisons can then be made between the three modeled outcomes and the experimentally observed inerting levels. This methodology has the potential to assist in ascertaining whether or not inertant decomposition plays a significant role in mitigation of flame propagation.

To prevent decomposition of the inertant by the computer model, two fictitious elements were created – one for each inertant – and entered into the CEA 400 database. This approach is similar to the one for non-reactive carbon described above. Each fictitious element had the respective thermochemical properties of monoammonium phosphate and sodium bicarbonate. However, they had the reactivity of a noble gas (chemically inert like helium). The likelihood of limestone undergoing calcination during the time scale of an explosion is very small; therefore, limestone was also treated in all cases as chemically inert for the purposes of the model.

Sodium bicarbonate and monoammonium phosphate were placed as chemical species into the CEA 400 computer program's compound database. This permitted the inclusion of these species in the input file, and the species could be considered as reactants or products by the CEA 400 program. The computer program could then decompose the

species (all or in part) in its chemical equilibrium calculations if warranted to minimize the Gibbs free energy for the system.

To force both species to decompose fully, each chemical species was inserted into the input file for the CEA 400 computer program. The information supplied was the molecular formula and the heat of formation data. All other thermochemical information were omitted for these two chemical species. By placing this information in the input file the computer program ignores thermochemical information (C_p , H° , S°) found in the database. Since only heat of formation data are provided in the input file, the CEA 400 computer program fully decomposes the “reactant”.

5.5.4 *Beta Factor*

A limitation of the CEA 400 program in calculating the adiabatic flame temperature is that it does not include any reaction kinetics in its calculation of equilibrium species. Thus, the assumption is that the reaction has an infinite amount of time to reach equilibrium. However, explosions occur on a finite timescale. The combustion propagation wave is actually a moving chemical reactor, and spends only a finite amount of time in a region of unburned reactants, leaving behind unburned reactants and products as it passes through. For the combustion of gases, where the actual reaction time is relatively short, the CAFT model predictions are good.

However, dusts must eject volatile material before homogeneous combustion can occur. If the combustion wave propagation is significantly faster than this added devolatilization step, the dust particle may not be able to expel all the volatile material before the combustion wave has passed through. The excess volatile matter expelled after the wave passes does not take part in the combustion reaction. In effect, the combustion wave rides along the crest of a near-stoichiometric volatile/oxidant mixture (Hertzberg *et al.* 1984, 1986). The stoichiometric volatile material acts as the fuel and the solid material (which does not have sufficient time to react within the combustion wave) acts as an inertant. As a result, the computer program fails to predict accurately the adiabatic flame temperature since it assumes that all the fuel present will react.

To account for this discrepancy, Hertzberg *et al.* (1984, 1986) devised the concept of a β -Factor, or the fraction of the volatile matter present in the mixture that has sufficient time to be expelled from the solid matrix to take part in the combustion process. The β -Factor ranges in value from 1 at low fuel concentrations (near the minimum explosible concentration or MEC) and approaches 0 at high concentrations. The excess volatile material is ignored and excluded from the system calculations.

The β -Factor can be used to explain the differences in explosion pressure observed between gas and dust explosions as a function of concentration. For gases the explosion overpressure increases as gas concentration increases, reaching a peak near stoichiometric concentrations. The overpressure then decreases as the fuel concentration is increased further. The excess fuel (above stoichiometric) acts as an inertant quenching the flame, thus forming an upper flammable limit. For dust, however, an upper flammable limit is not observed in the usual concentration ranges tested. The explosion overpressure increases as fuel concentration increases, but after reaching a maximum value remains constant or decreases slightly as the amount of fuel increases further. Using the β -Factor interpretation, the excess volatile matter (gaseous fuel) which would lead to an upper flammable limit in gas/air combustion does not contribute in a dust explosion system. The combustion wave propagates too quickly through the dust cloud, relative to the devolatilization process. The combustion wave has moved on and the volatile matter is introduced to the system outside the “moving reactor”.

5.5.5 *Current Approach to the β -Factor*

The implementation of the β -Factor in the current model is different than that found in Hertzberg *et al.* (1984, 1986). In their model, the β -Factor was adjusted so as to modify the volatile concentration to keep the explosion overpressure at the maximum value (i.e. volatile concentrations near stoichiometric). This would mean that the β -Factor would have a value of unity at low concentrations (below stoichiometric levels), with all the volatile material reacting; as more dust was added to the combustion chamber, the factor would have to be lowered to keep the volatile/air mixture at stoichiometric levels. This approach, however, resulted in calculated overpressures that were greater than those

observed experimentally. The authors attributed the difference to the less than adiabatic combustion in the explosion chamber (heat losses to the surroundings, wall quenching and buoyancy distortions of the explosion fireball). Using this previous method, the β -Factors as a function of concentration would be constant for a given fuel regardless of the type of test chamber used to obtain experimental overpressure values. This would also imply that the inerting level determined by this previous model would be vessel independent.

Because one of the objectives in the present work is to construct a model to predict the inerting level in a given type of explosion chamber, the universal β -Factor approach is not appropriate. Test condition factors, such as vessel size and geometry and ignition source strength, that influence the non-adiabatic combustion in each explosion vessel (20-L and 1-m³) would also influence the determination of the inerting level in each. Additionally, material factors such as particle size, porosity, and surface oxidation would be factors that need to be considered. Therefore, for our purposes the material factors and the test condition factors were considered in aggregate and are also included in the β -Factor. This makes the β -Factor as a function of concentration unique to each test chamber (20-L and 1-m³) and dust sample. To accomplish this, the fraction of volatile matter available for combustion in the system (the β -Factor) is adjusted so that the CEA 400 computer program produces overpressures that match the experimentally observed overpressure.

Figure 5.1 is an example of the explosion overpressure plotted against aluminum concentration in the 20-L chamber and the 1-m³ chamber. (All experimental data are from Dastidar and Amyotte, 2002.) The solid line represents calculated constant volume overpressure for the system with all volatile material participating in combustion. In the upper graph of Figure 5.1, the solid squares represent the experimentally determined overpressure in the 20-L chamber. The procedure now requires that the volatile component be multiplied by a β -Factor such that the resulting overpressure matches the experimentally observed value by keeping the “volatile” component at or below stoichiometric levels. The following equation describes the procedure:

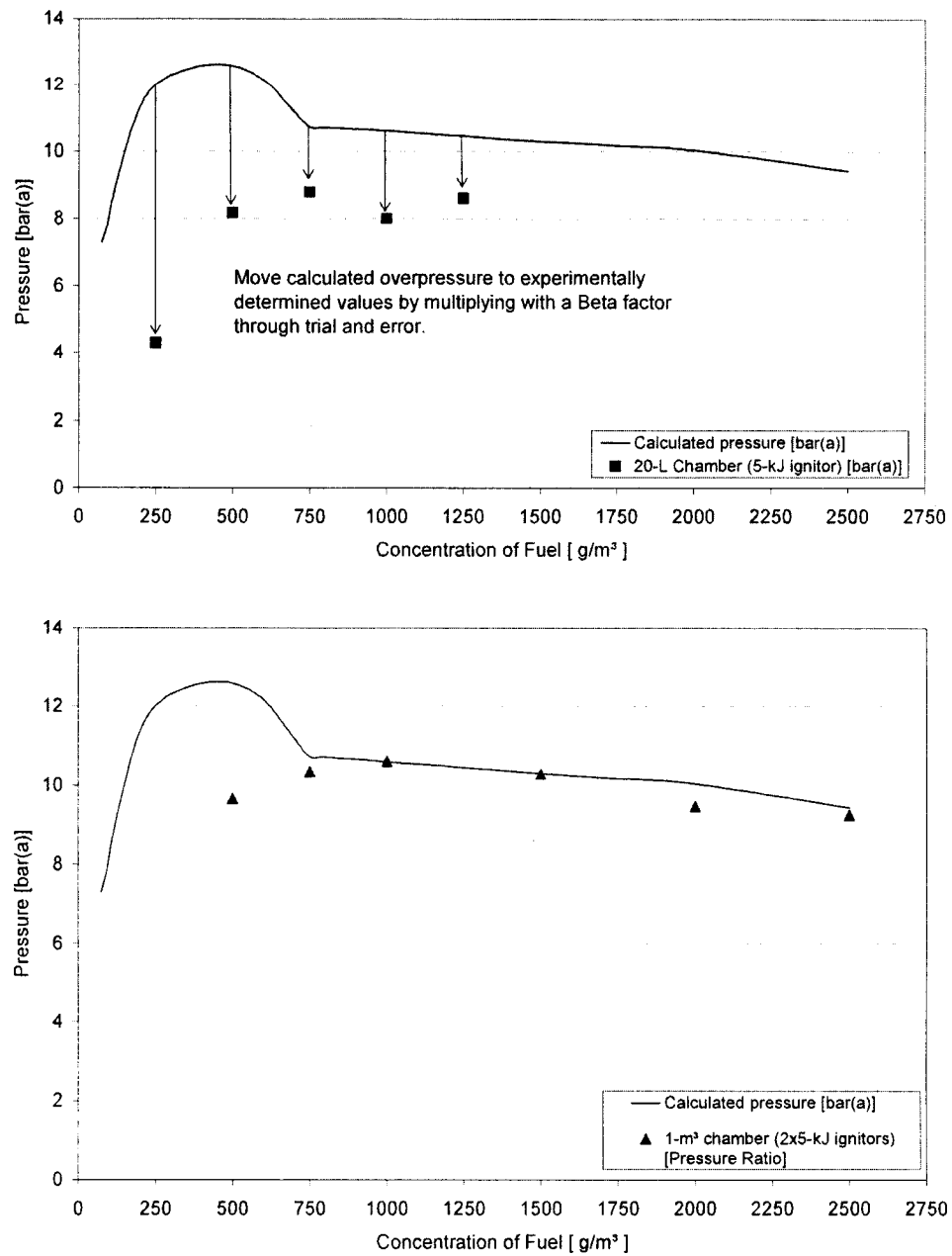


Figure 5.1: Comparison between calculated overpressures with experimentally determined overpressures for aluminum.

$$(4) \quad \left(\begin{array}{c} \text{Moles of volatile material} \\ \text{present in the system} \end{array} \right) \times \beta = \left(\begin{array}{c} \text{Moles of volatile material that} \\ \text{produce observed overpressure} \end{array} \right)$$

Trial and error is used to determine the value of β . Note that in both graphs of the figure, the calculated overpressure is the same, but the experimentally determined values differ between the chambers. The difference is likely due to wall quenching effects in the smaller chamber.

Figure 5.2 shows the determined β -Factor as a function of concentration for both chambers. The β -Factor is higher at low concentrations and decreases as fuel concentration increases. A smaller percentage of the available volatile material contributes to the combustion process, thereby keeping the explosion overpressure in the system high. The β -Factor decreases as the fuel concentration increases in both chambers, even though from Figure 5.1 (lower graph) it appears unnecessary for the aluminum dust in the 1-m³ chamber where the calculated overpressures are close to the experimental values. This is because the excess aluminum (amount in excess of the stoichiometric aluminum/air mixture) acts as an inertant helping to cool the flame. The β -Factor adjusts the volatile concentration keeping it near stoichiometric or below.

The β -Factors for the other dusts (anthraquinone, polyethylene, cornstarch and coal dust) were determined in a similar fashion. An important point to note in the determination of the β -Factor for the carbonaceous dusts is that at high concentrations the computer calculated system pressure initially decreased after a stoichiometric concentration was achieved, but then continued to gradually increase. This phenomenon may be attributed to pyrolysis of the unburned volatile matter to gaseous hydrocarbons. Additionally, in most cases the calculated peak overpressure of the dust combustion was higher than that observed experimentally, thus indicating that dust cloud combustion in the experimental test apparatus is less than adiabatic. Only in the case of anthraquinone combustion in the 20-L chamber was the experimental peak overpressure higher than that of the calculated

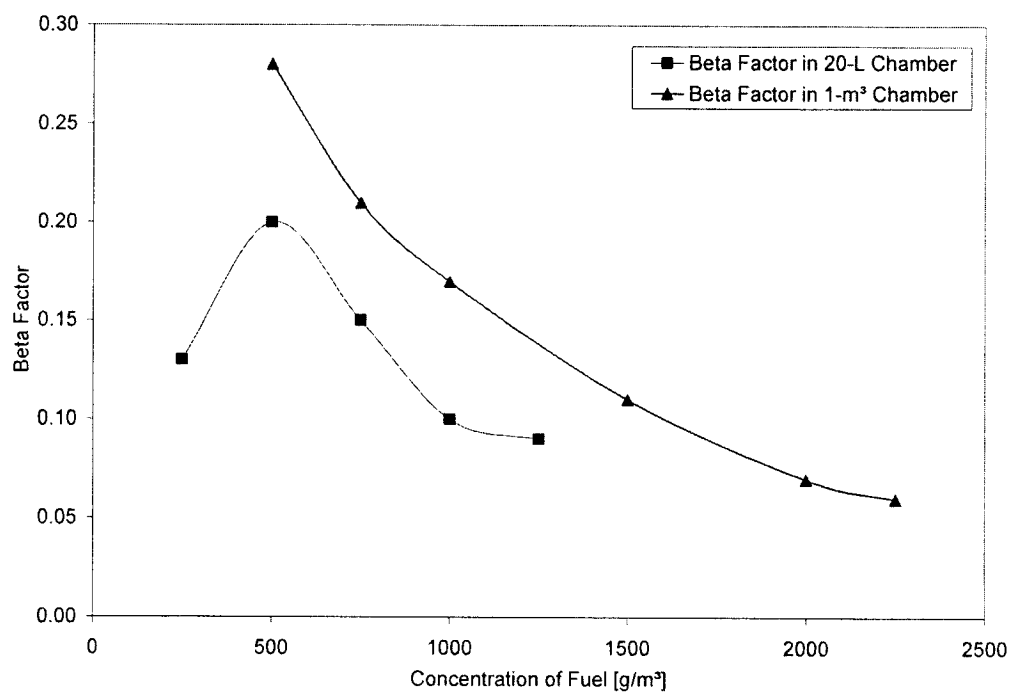


Figure 5.2: β -Factor as a function of aluminum concentration.

peak overpressure. This may possibly be due to the strong ignition source used for the test overdriving the reaction and producing a higher pressure for this particular material.

5.5.6 *Selection of Test Condition*

There were two test conditions used for the model. To determine the β -Factors, constant volume conditions were chosen. As previously described, this allowed for comparisons between experimental overpressures and calculated overpressures; the β -Factor was derived from these comparisons.

Even though model results are compared to constant volume experimental results, calculations to determine the limit flame temperature and the inerting level were performed in a constant pressure test condition. Constant volume conditions could have been used; however, the computational load would have been significantly greater since the system density would have to be recalculated at every fuel/inertant/air mixture concentration. Since only the limit temperature of flame propagation is to be used, calculations based on pressure increase in a fixed volume are not necessary.

To determine the inerting level, a heat balance approach similar to Sapko *et al.* (1998), Hertzberg *et al.* (1984, 1986), Richmond, *et al.* (1975, 1977), and Moore (1980) was used. The concept is relatively simple; first, the fuel/air combustion reaction generates heat. The inertant in the mixture abstracts heat from the system, preventing flame propagation when the flame temperature is reduced below the limit value. A trial and error method is used to determine the amount of inertant required to prevent combustion since the CEA 400 program does not permit back calculation of the required inertant quantity from a given flame temperature. This trial and error method is time consuming, but by using a constant pressure test condition the repetitive calculation of the initial system density of the mixture is avoided.

5.5.7 *Selection of the Limit Flame Temperature*

The limit flame temperatures for the dusts tested were determined in a manner similar to that for determining the limit flame temperature for gases. The constant pressure flame temperature of the fuel/air mixture was determined as a function of fuel concentration.

Then, using the experimentally derived limit fuel concentration for flame propagation (i.e. lower flammable limit for gases and minimum explosible concentration for dust) the limit temperature can be determined. This limit temperature is then used to determine the inerting level. Figure 5.3 shows the graph used to determine the limit flame temperature for aluminum. The limit flame temperatures for the other fuel dusts were obtained in a similar manner. Factors which would affect limit flame propagation conditions such as dust particle size and moisture content would not influence a theoretically derived, or averaged, limit flame temperature. By utilizing the experimentally determined minimum explosible concentration to establish a unique material specific limit flame temperature, these factors are, in part, accounted for.

From Figure 5.3, the limit flame temperature for aluminum combustion based upon a minimum explosible concentration (MEC) of 80 g/m^3 (Hertzberg *et al.*, 1992) is 2000 K. The limit flame temperature for anthraquinone combustion, based upon an experimentally determined MEC of 45 g/m^3 , is 1200 K. The limit flame temperature for polyethylene combustion, based upon an MEC of 30 g/m^3 (ASTM E 1515, 2003), is 1250 K. The limit flame temperature for cornstarch, based upon an experimentally determined MEC of 85 g/m^3 , is 1200K. Finally, the limit flame temperature for coal dust, based upon an MEC of 80 g/m^3 (ASTM E 1515, 2003), is 1450 K.

5.5.8 *Modification of Reactants and Construction of a Flammability Envelope from Calculations*

Model calculations were then performed on a given reactant mixture to determine the inerting level. The reactant mixture is comprised of the moles of fuel (with applicable β -Factor applied), moisture (if present in the proximate analysis of the fuel), inertant and air for each experimental concentration. The mixture fuel concentration was selected to coincide with actual experiments (Dastidar and Amyotte, 2002): 125, 250, 500, 750, 1000, 1250, 1500, 1750, 2000, and 2500 g/m^3 of fuel, to which inertant was added. The adiabatic flame temperature of this mixture was then determined by the CEA 400 computer program. If this temperature is below the limit flame temperature, the quantity of inertant present is sufficient to inhibit flame propagation.

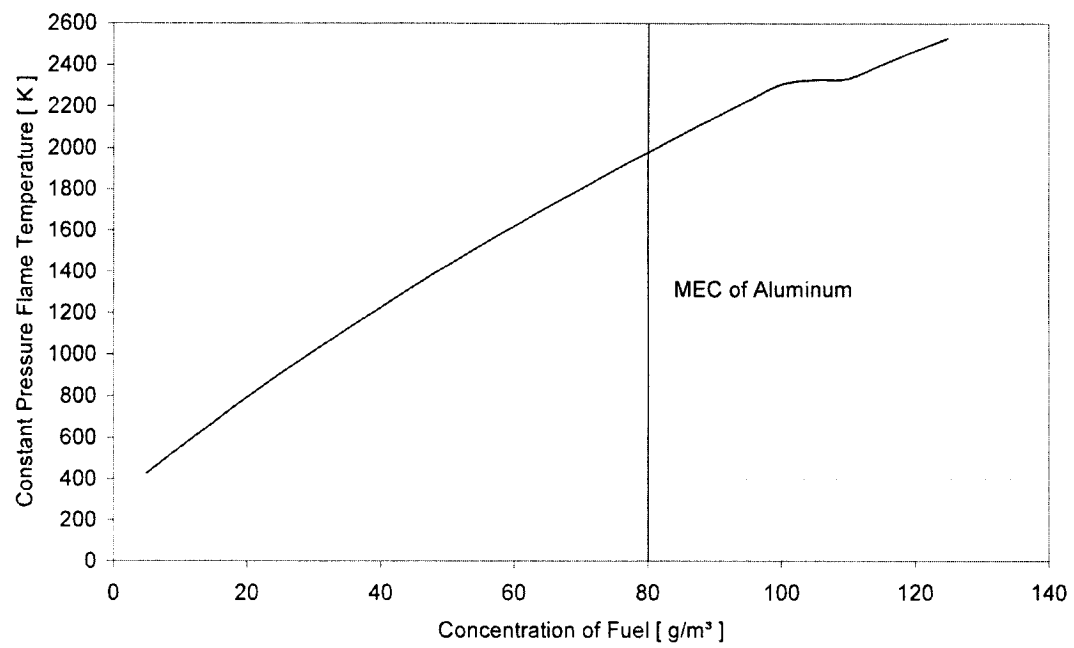


Figure 5.3: Determining the limit flame temperature for aluminum combustion based on an MEC value of 80 g/m³.

The general procedure to find the inerting level initially uses a very high concentration of inertant (99% inertant in the fuel/inertant mixture). If the flame temperature is below the limit temperature (no combustion), the inertant percentage is reduced by 1% by mass (i.e. 98% inertant in the fuel/inertant mixture) and the flame temperature is recalculated. The moles of fuel (with β -Factor applied), moles of moisture, and moles of air remain constant. This procedure continues until the calculated flame temperature of the mixture is greater than the determined limit flame temperature. The highest inertant quantity that produces the highest adiabatic flame temperature without exceeding the limit flame temperature is considered to be the inerting level.

By plotting the highest inertant concentration required to produce an adiabatic flame temperature that is just below the limit flame temperature, against the concentration of fuel used, an inerting envelope is obtained. The concentration of fuel used for the plots is the “whole” fuel that would be placed in the experimental chamber (i.e. 125 g/m³, 250 g/m³, etc.), not the β -Factor adjusted concentration of volatiles. This procedure was followed for all fuels used in the experiments (both 20-L and 1-m³), for all experimental concentrations of fuel, and for all inertants used in the experiments. As previously discussed, limestone was treated at all times as chemically inert, while sodium bicarbonate (SBC) and monoammonium phosphate (MAP) were analyzed under three different conditions: chemically inert “(i)”, partially decomposed “(p)” and fully decomposed “(d)” (nomenclature as given in subsequent figures). The decision to include the latter two inertant conditions was based on the possibility that under experimental test conditions for dust explosion inerting, some degree of combustion of the dust cloud is usually possible in the vicinity of the ignition source. Under such circumstances the additional heat abstraction from the decomposition of the inertant may assist in quenching flame propagation.

5.6 MODEL RESULTS AND DISCUSSION

The results of the CAFT model calculations are presented in Figures 5.4 through 5.15. There are three graphs in each figure. The first two graphs compare the experimental inerting levels determined in the 1-m³ chamber (standard reference volume) with inerting

levels obtained from the CAFT model (calculated using β -Factors determined from both the 1-m³ and the 20-L experimental overpressures, respectively). A ratio of the experimentally determined fuel-independent inerting level and the model derived value is given to the right of each figure. This ratio is further discussed in the following two paragraphs. The third graph in each figure plots the errors for each of the two graphs above – i.e. the ratio of the actual inerting level to that calculated using the model at the given concentrations of fuel used.

While the objective of the CAFT model is to predict the individual inerting level at a given concentration of fuel, it would also be beneficial if the model were able to predict the Minimum Inerting Concentration (MIC) – the least amount of inertant required to inert a dust explosion regardless of the fuel concentration. The MIC can be useful in the design and implementation of explosion suppression systems for a dust handling facility. A full description of the MIC can be found in Dastidar *et al.* (1998c, 1998d, 1999) and Dastidar and Amyotte (2002). The advantage of using the CAFT model would be to minimize the number of experiments needed to determine the MIC for a given fuel and inertant mixture (effectively using the model as a screening tool).

To assist in this analysis, a ratio is given next to the upper two graphs in each figure. This is the ratio of the experimentally determined MIC to the MIC obtained from the CAFT model. In cases where, experimentally and/or computationally, a definitive MIC was not observed, the highest concentration inerting level (HV) was used. Ratios close to unity indicate that the actual MIC and the model predicted MIC are in good agreement. It should be noted that the CAFT-model MIC (or HV) might not occur at the same concentration of fuel dust as the MIC obtained from experiments. As a result, this form of examination differs from the analysis provided by the bottom graph of each figure.

5.6.1 Mitigation Results for Aluminum Dust Explosions

Depicted in Figures 5.4 and 5.5 are the model results for the inerting of atomized aluminum powder with sodium bicarbonate and monoammonium phosphate,

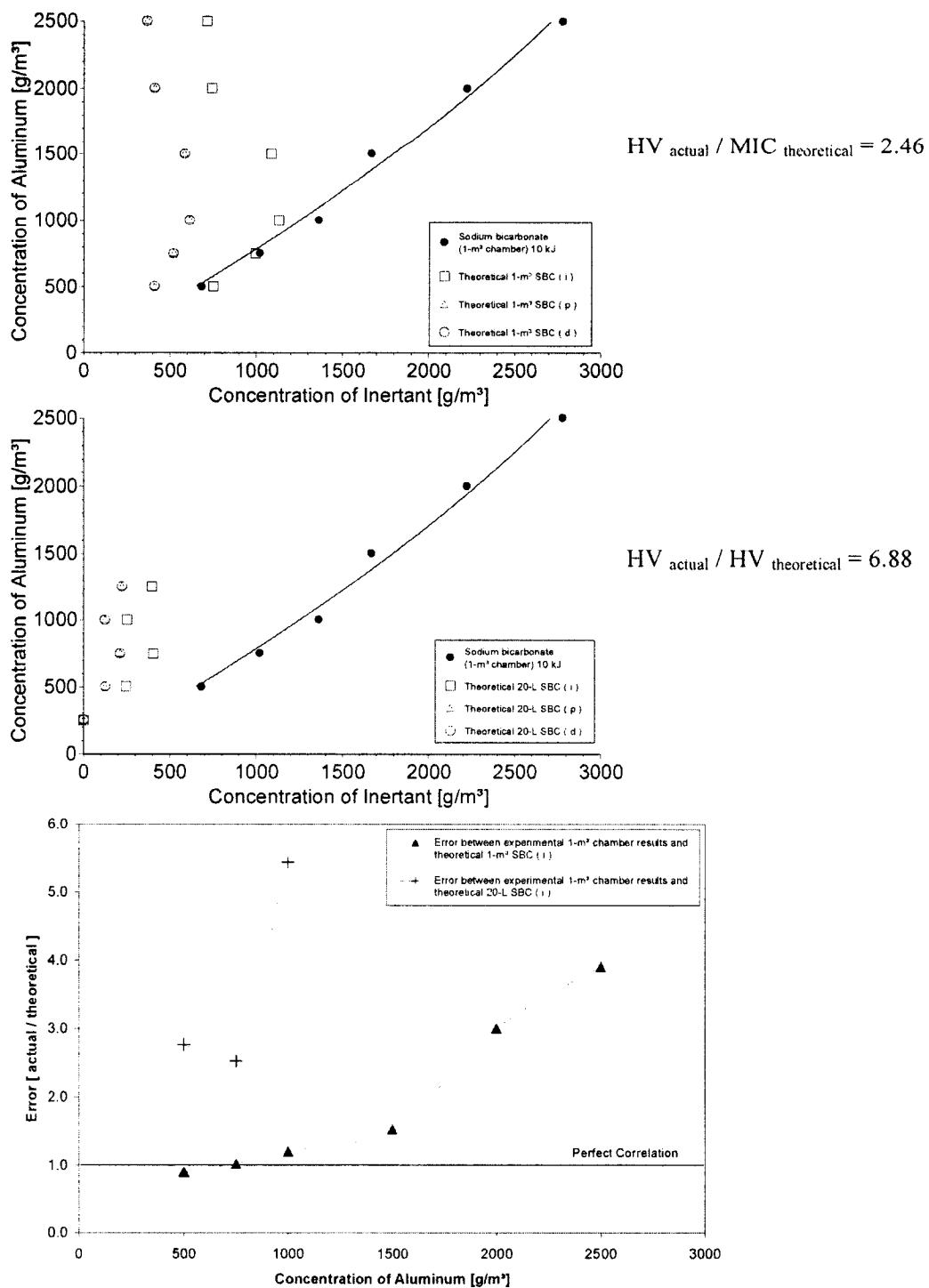


Figure 5.4: Inerting aluminum with sodium bicarbonate.

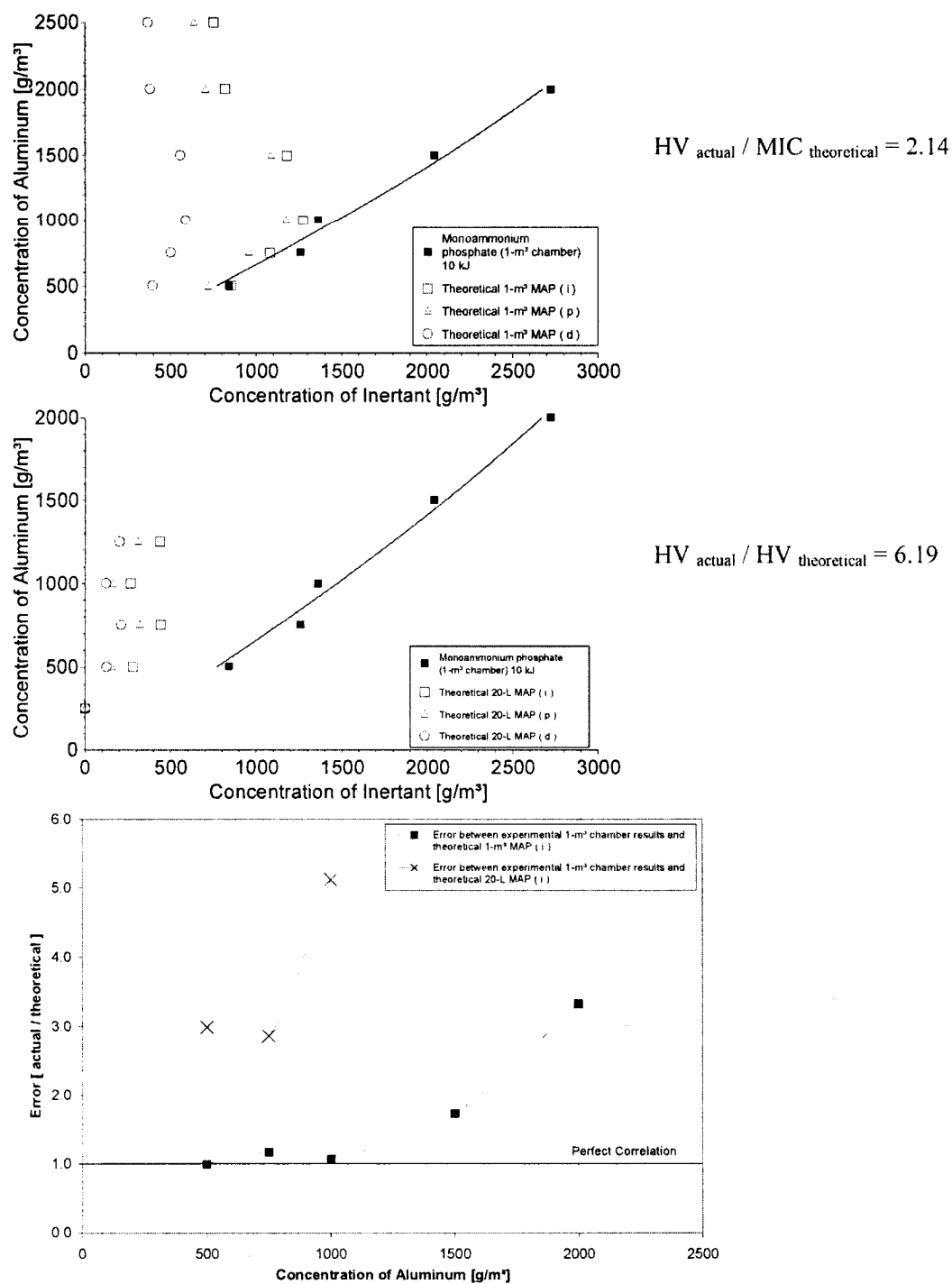


Figure 5.5: Inerting aluminum with monoammonium phosphate.

respectively. In both figures it can be seen that the 1-m³ CAFT model (upper graph) yields calculated inerting levels similar to the experimental inerting levels at low fuel concentrations. The 20-L CAFT model results (middle graph) are clearly not in agreement with the experimental inerting levels shown in Figures 5.4 and 5.5. The degree of error (inerting level agreement) can be seen in the bottom graph of each figure. The error levels of the 1-m³ CAFT model results are significantly lower than the 20-L results at lower fuel concentrations. It should be noted that the presence of the inertant may influence the amount of fuel able to participate in the combustion process by abstracting heat and preventing devolatilization. This in effect would act to further decrease the β -Factor values that were determined by adjusting the theoretical explosion overpressure to match the experimental explosion overpressures of the pure fuel. While this may improve the correlation of the model results with the experimental values, the inclusion of this effect would require back calculation of the β -Factor at each fuel concentration for each inerting level and would remove the utility of this model as a predictive tool since the inerting levels would have to be determined before the β -Factor could be derived.

In both figures the 1-m³ CAFT model results show an inerting envelope with a distinct “nose” forming an MIC, whereas the experimental results did not produce an MIC. The ratio of the actual experimental maximum inerting level to the model predicted value is large. In both figures, the non-reacting inertant, “(i)”, produced inerting levels closer to experimental values than either the partially reactive inertant, “(p)”, or decomposed inertant, “(d)”.

As mentioned, the 20-L CAFT model results in Figures 5.4 and 5.5 compare poorly with the experimental values. There was no MIC produced by the model (over the range of concentrations for which 20-L data were available), and the maximum inerting level is approximately seven times that of the model-derived maximum inerting level. The poor performance of the 20-L CAFT model may be attributed to comparably lower overpressures and rates of pressure rise observed in the 20-L chamber explosibility data than the 1-m³ chamber data. The volume of the smaller chamber may have contributed to quenching of the aluminum combustion, thereby lowering the pressure output. This in turn would influence the calculated β -Factors in the 20-L CAFT model.

5.6.2 Mitigation Results for Anthraquinone Dust Explosions

Figures 5.6 and 5.7 show graphs of the CAFT model and experimental inerting levels for the inerting of anthraquinone with sodium bicarbonate and monoammonium phosphate, respectively. Here, the model performs reasonably well for both volumes. The error ratio over a moderate dust concentration range is relatively low in both cases, and as in the case of aluminum, the non-reactive inertant produced better results. (As an illustration, see the bottom graph in Figure 5.7 and compare the 20-L (i) and (d) curves.)

In Figure 5.6, there is a distinct inerting envelope with an MIC in the experimental results, but only the 1-m³ CAFT model results produce a similar enclosure. The 20-L CAFT model failed to predict an inerting envelope but did produce maximum inerting levels similar to experimental values, thereby better predicting the inerting performance of the inertant. The influence of wall quenching on dust cloud combustion was not observed in the 20-L chamber for the explosibility testing of anthraquinone (Dastidar and Amyotte, 2002); therefore, the extremely low inerting level predictions seen with aluminum in Figures 5.4 and 5.5 are not evident with anthraquinone in Figures 5.6 and 5.7.

5.6.3 Mitigation Results for Polyethylene Dust Explosions

The CAFT model results for the inerting of polyethylene dust with sodium bicarbonate and monoammonium phosphate are depicted in Figures 5.8 and 5.9, respectively. In this case, the 20-L CAFT model provides a better prediction of the experimental inerting levels than the 1-m³ CAFT model results. This occurrence is due to the low β -Factors calculated for high concentrations of polyethylene in the 1-m³ chamber; the model produced high overpressures at elevated fuel concentration due to pyrolytic decomposition of polyethylene. Additionally, low experimental overpressures were observed in the 1-m³ chamber at elevated fuel concentrations (Dastidar and Amyotte, 2002), possibly indicating an approach to the upper explosible limit for polyethylene in this chamber volume. As a result, low participation factors were required by the model to match experimental overpressures.

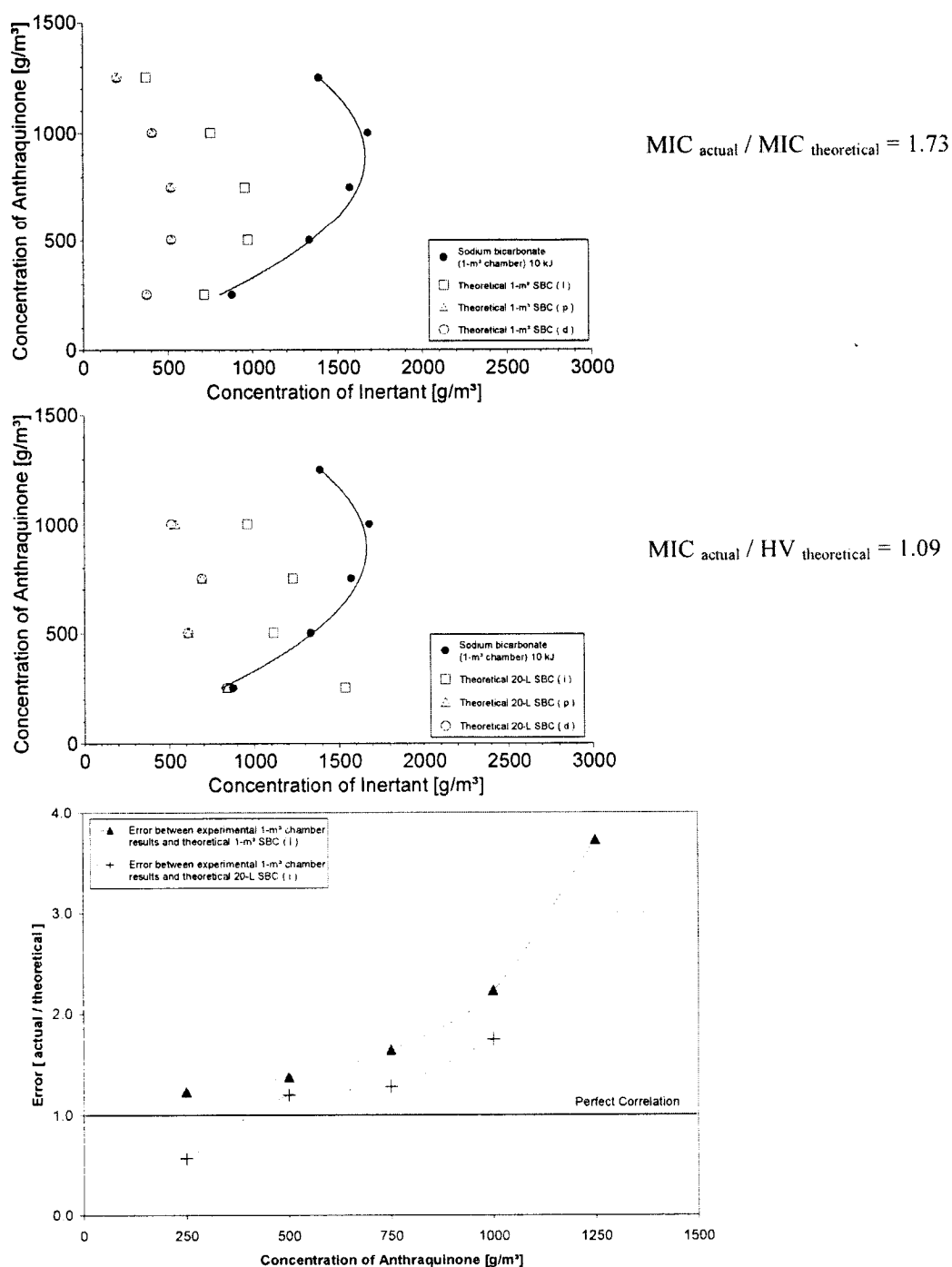


Figure 5.6: Inerting anthraquinone with sodium bicarbonate.

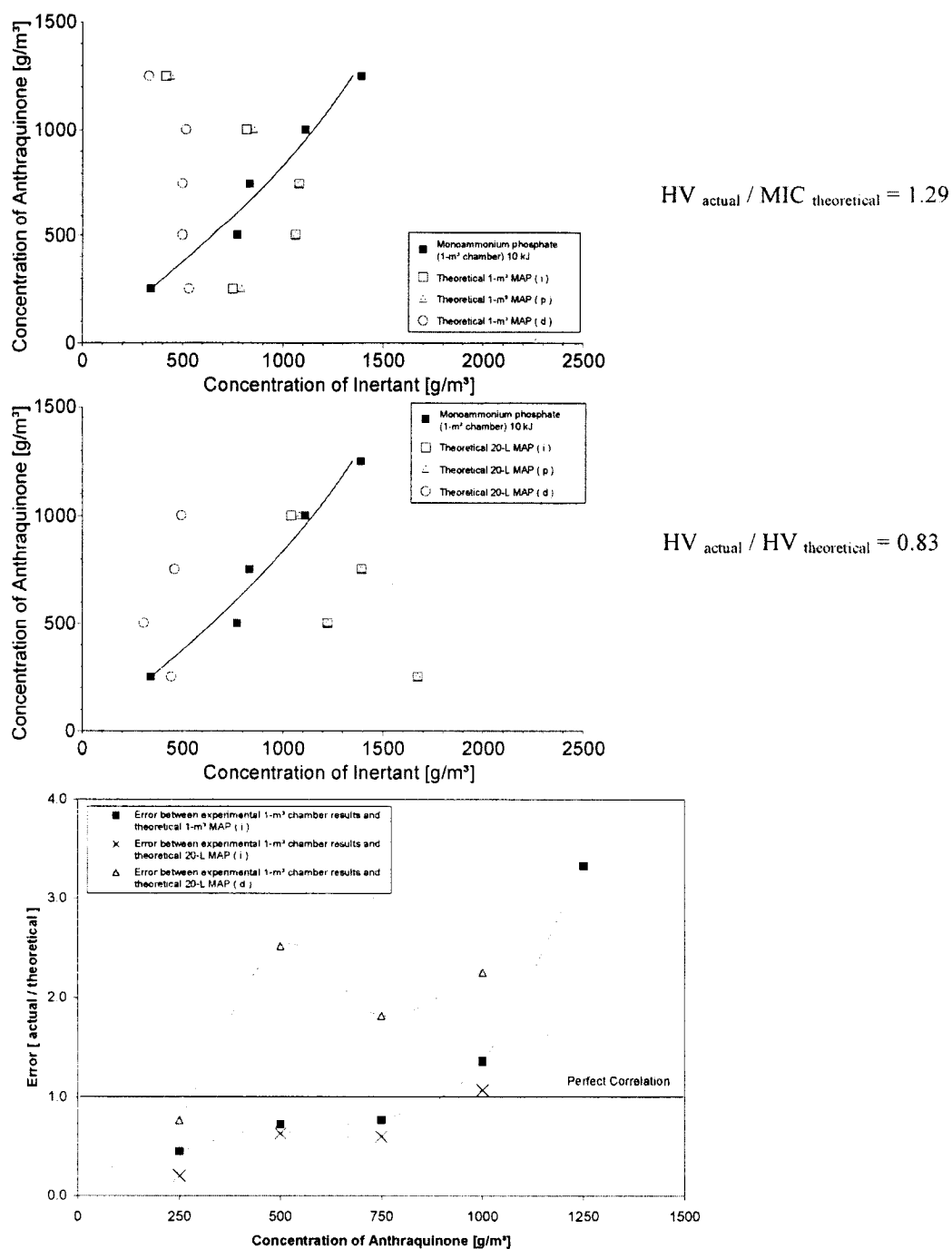


Figure 5.7: Inerting anthraquinone with monoammonium phosphate.

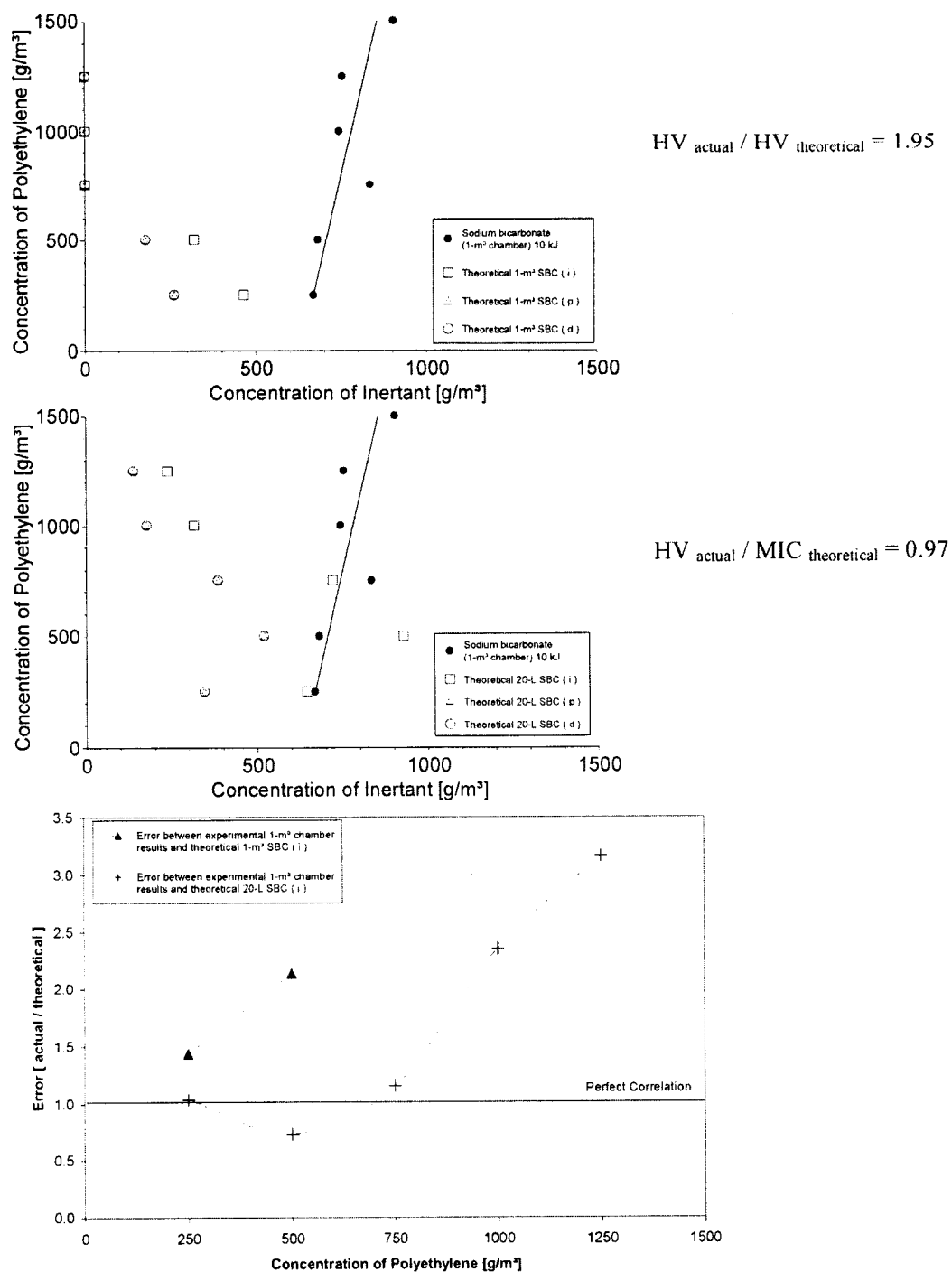


Figure 5.8: Inerting polyethylene with sodium bicarbonate.

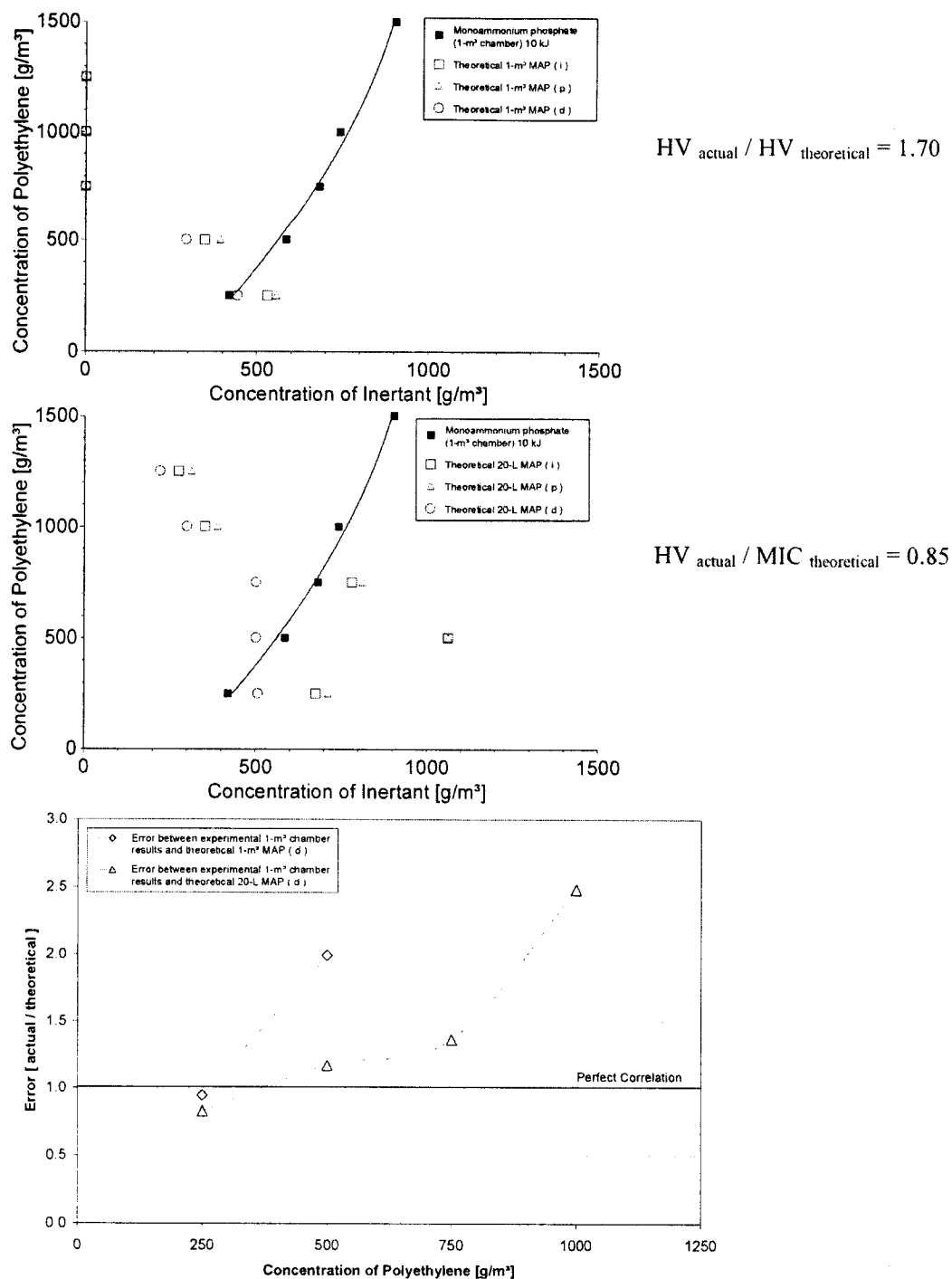


Figure 5.9: Inerting polyethylene with monoammonium phosphate.

These low experimental overpressures were not observed in the 20-L chamber, so the β -Factors here were not as low as those calculated for the 1-m³ CAFT model. Thus, the 20-L CAFT model was a better predictive tool for determining the maximum inertant requirement than the 1-m³ CAFT model (ratios near unity in Figures 5.8 and 5.9). As with aluminum and anthraquinone, the non-reacting inertant models for polyethylene explosion mitigation produced inerting levels closer to experimental values than the partially or completely decomposed inertant models.

5.6.4 Mitigation Results for Cornstarch Dust Explosions

Figures 5.10, 5.11 and 5.12 depict the inerting of cornstarch with sodium bicarbonate, monoammonium phosphate and limestone, respectively. In Figures 5.10 and 5.11, both the 1-m³ CAFT model and the 20-L CAFT model performed equally in their ability to predict cornstarch explosion inerting requirements. While the predictions of experimental inerting levels are only modest, they are sufficiently accurate to be used as a predictive tool to minimize the number of experiments that need to be conducted.

Unlike the previous fuel dusts (aluminum, anthraquinone and polyethylene), with cornstarch the completely decomposed inertant model performed better than the non-reactant and partially decomposed inertant models. Given the inherent limitations of the CAFT approach, it would not be prudent to conclude from this observation that inertant decomposition is definitely occurring during the experiments. What can be concluded, however, is that this observation is consistent with the trend of the experimental data (Dastidar and Amyotte, 2002) in which the overall ranking of inerting requirements from greatest to least is: aluminum, anthraquinone, polyethylene, cornstarch and coal dust. The fact that aluminum requires more inert material to inhibit flame propagation than, for example, cornstarch, is a direct reflection of its higher burning velocity and hence higher rate of pressure rise (as well as explosion pressure). In other words, because cornstarch burns more slowly than aluminum dust, the explosion timescale may be long enough to permit the possibility of the inertant decomposing once it is heated to its decomposition temperature (thus affording the reacting mixture the additional heat sink effect of an endothermic heat of decomposition).

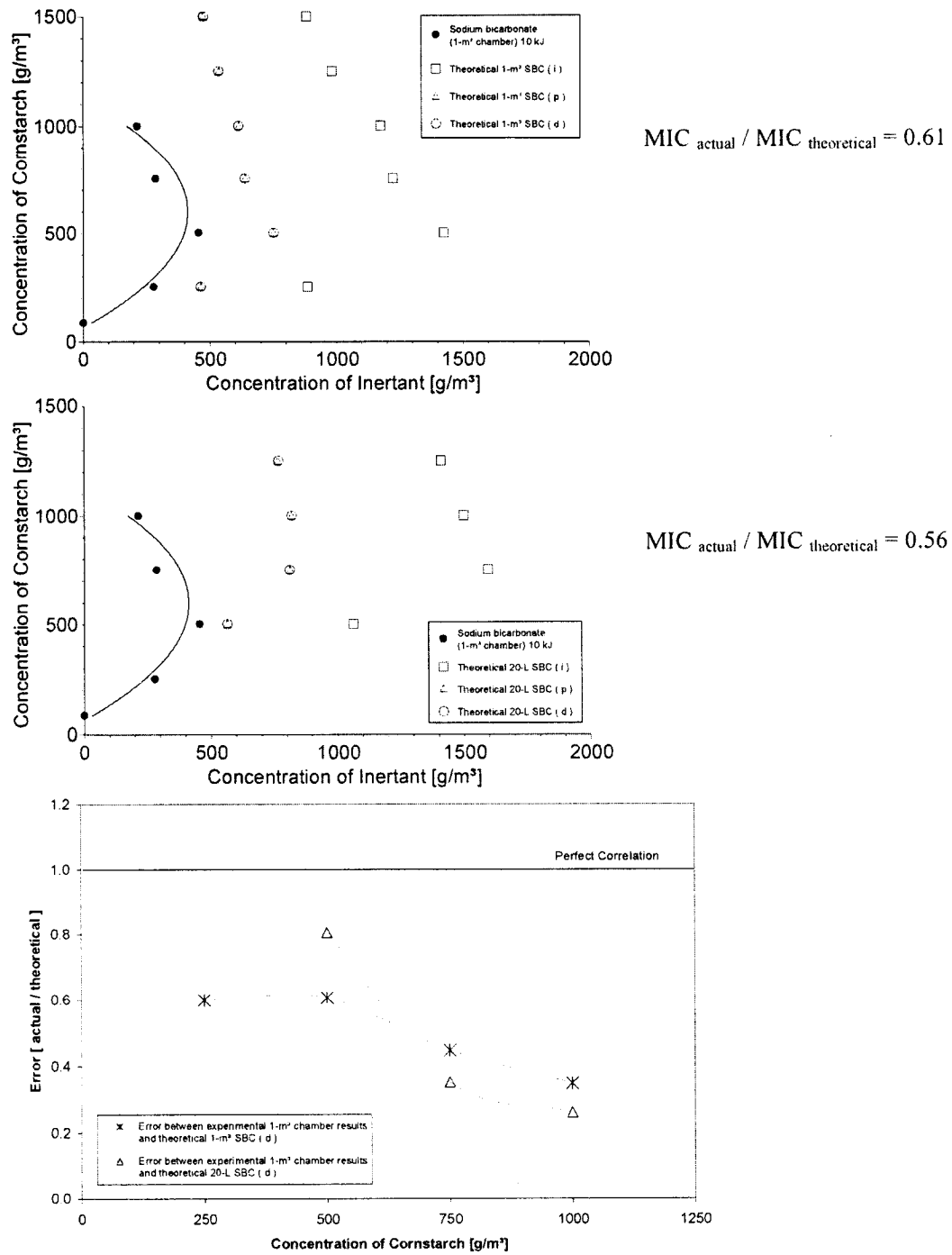


Figure 5.10: Inerting cornstarch with sodium bicarbonate.

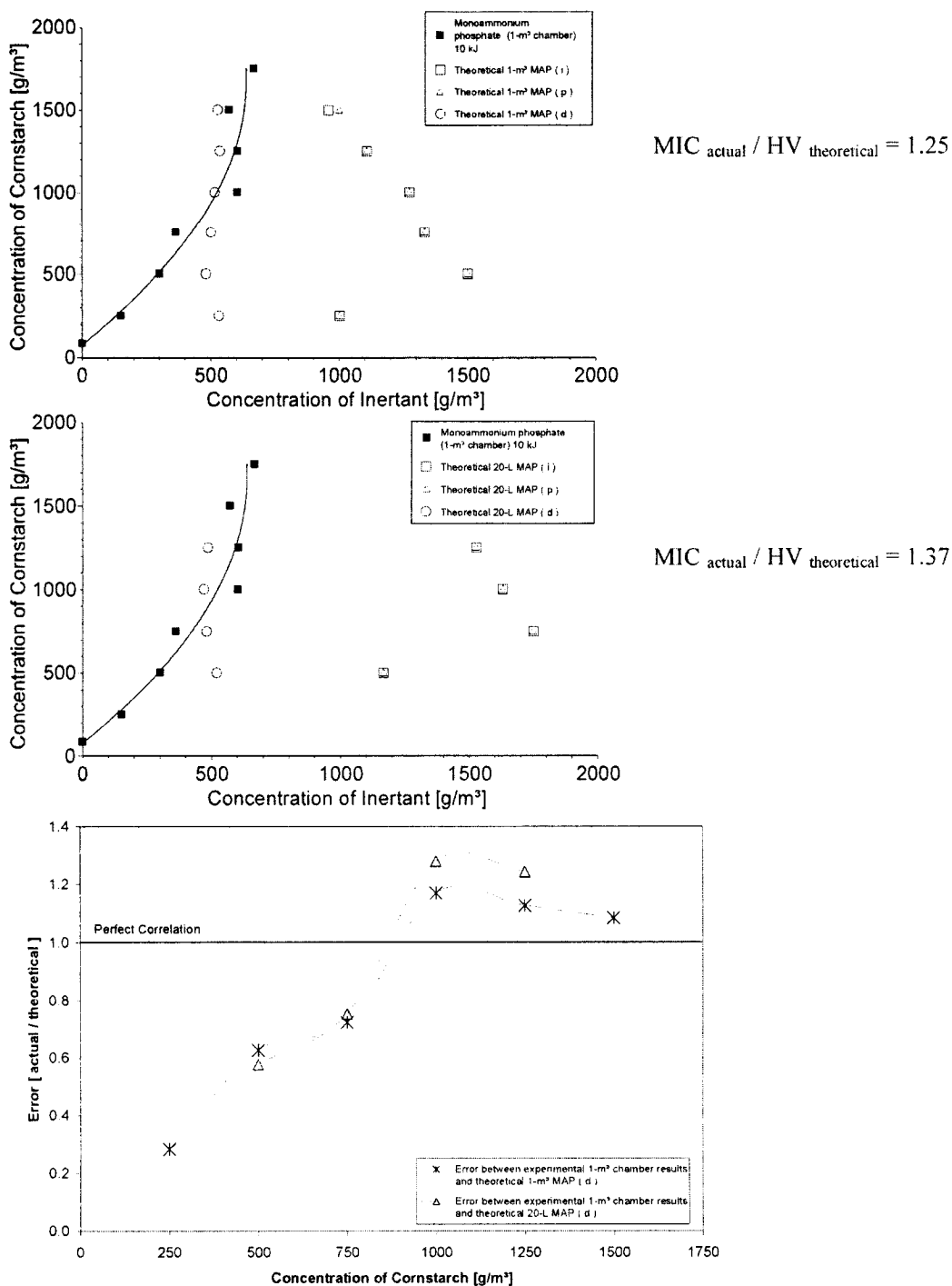


Figure 5.11: Inerting cornstarch with monoammonium phosphate.

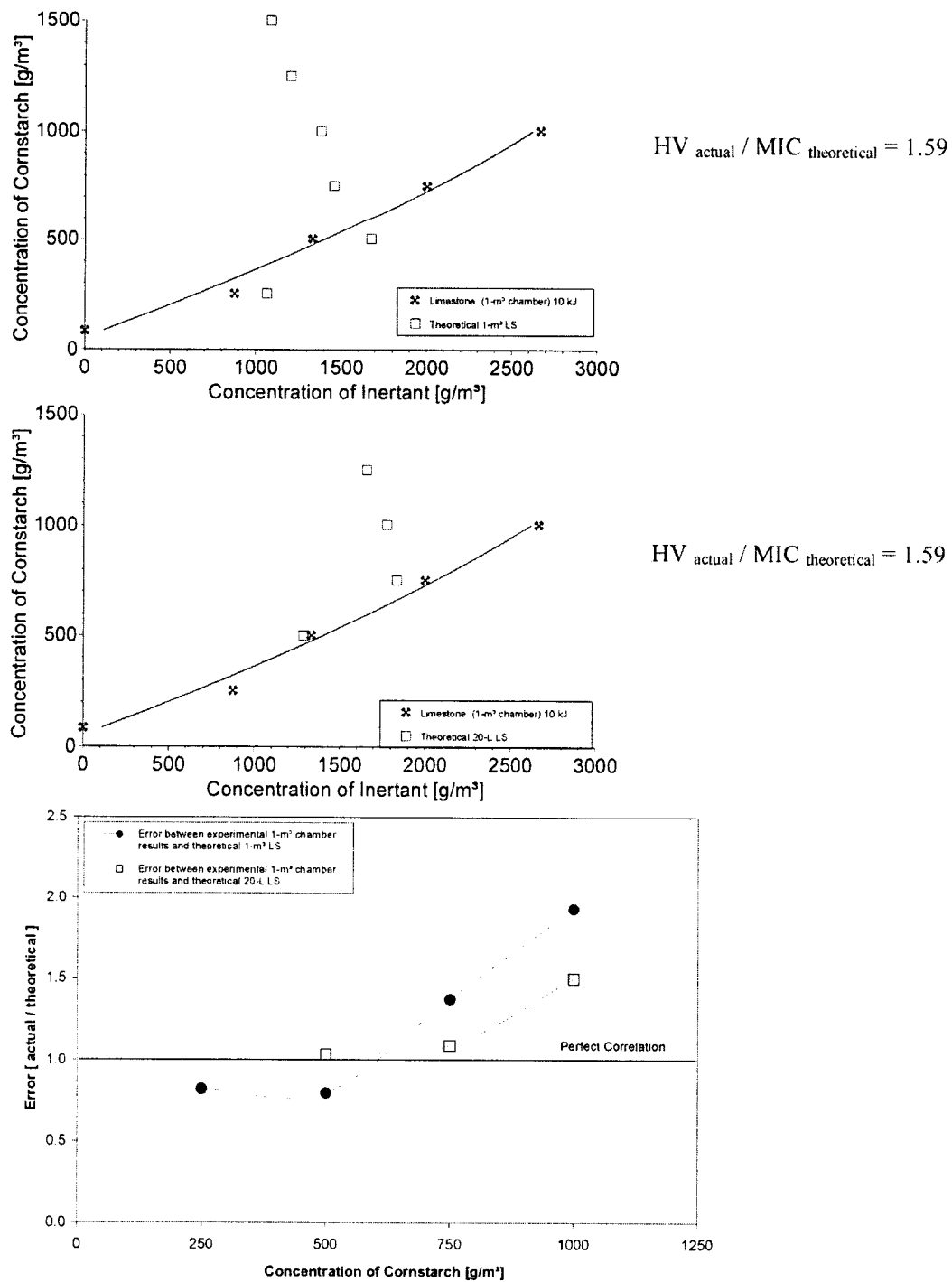


Figure 5.12: Inerting cornstarch with limestone.

In accordance with accepted empirical evidence, in Figure 5.12 only non-reactive limestone was used in the 20-L and 1-m³ CAFT models. In both cases, the model results agree well with the experimental results at low fuel concentrations. At higher fuel concentrations, the models predict lower inertant requirements than the experimental levels. This has also been seen in some of the other results previously discussed, and is likely a reflection of the difficulty in determining the β -Factor for fuel participation.

5.6.5 Mitigation Results for Pulverized Coal Dust Explosions

In Figures 5.13, 5.14 and 5.15, the model results for the inerting of coal dust with sodium bicarbonate, monoammonium phosphate and limestone, respectively, are presented. Arguments similar to those advanced with respect to Figures 5.10, 5.11 and 5.12 can be used to interpret these coal dust inerting results. It is interesting to note the occurrence of a predicted inerting envelope and MIC in Figure 5.15 (coal dust/limestone) as well as the relatively low error displayed by the 20-L CAFT model over the full concentration range (bottom graph in Figure 5.15). The 20-L chamber is widely used in our laboratory and others worldwide for investigation of the explosibility of coal dust/limestone mixtures.

5.6.6 Analysis of Model Performance

In addition to limitations in the determination of the β -Factor accounting for the errors between model and experimental results, there are two additional factors that need to be considered – both focusing on model limitations. First, the model predicts inerting requirements based only on thermal quenching and thus cannot take into account chemical inerting factors such as the mitigation of reaction kinetics by free radical capture. It has been theorized that monoammonium phosphate and sodium bicarbonate have some potential for chemical mitigation; this may account for some of the discrepancies observed between the modeled and experimental inerting levels reported in the current work.

Second, the model only takes into consideration partial participation of the fuel dust in the combustion cloud with the use of the β -Factor. It does not account for partial participation of the inertant in thermal quenching due to the limited timescale of

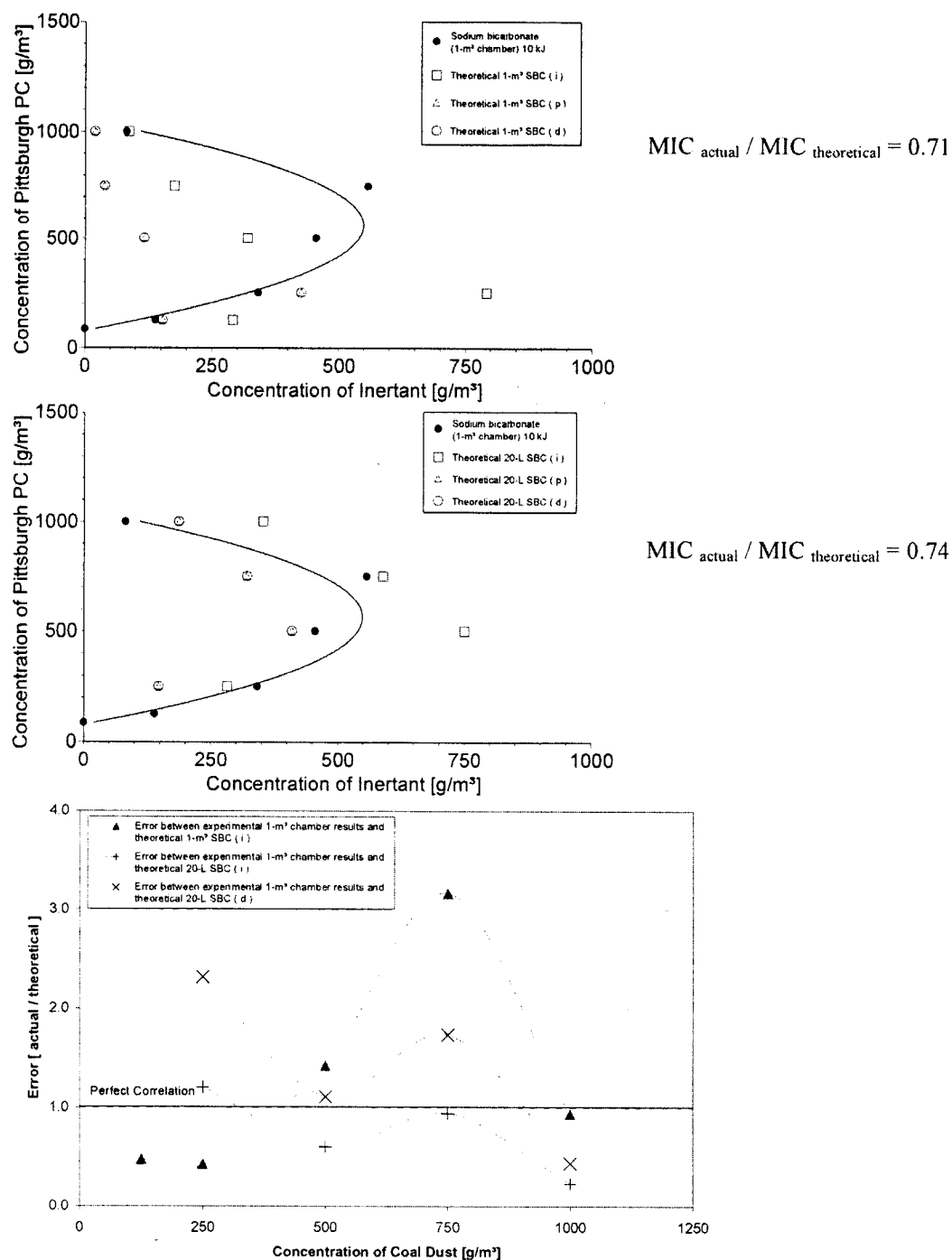


Figure 5.13: Inerting coal dust with sodium bicarbonate.

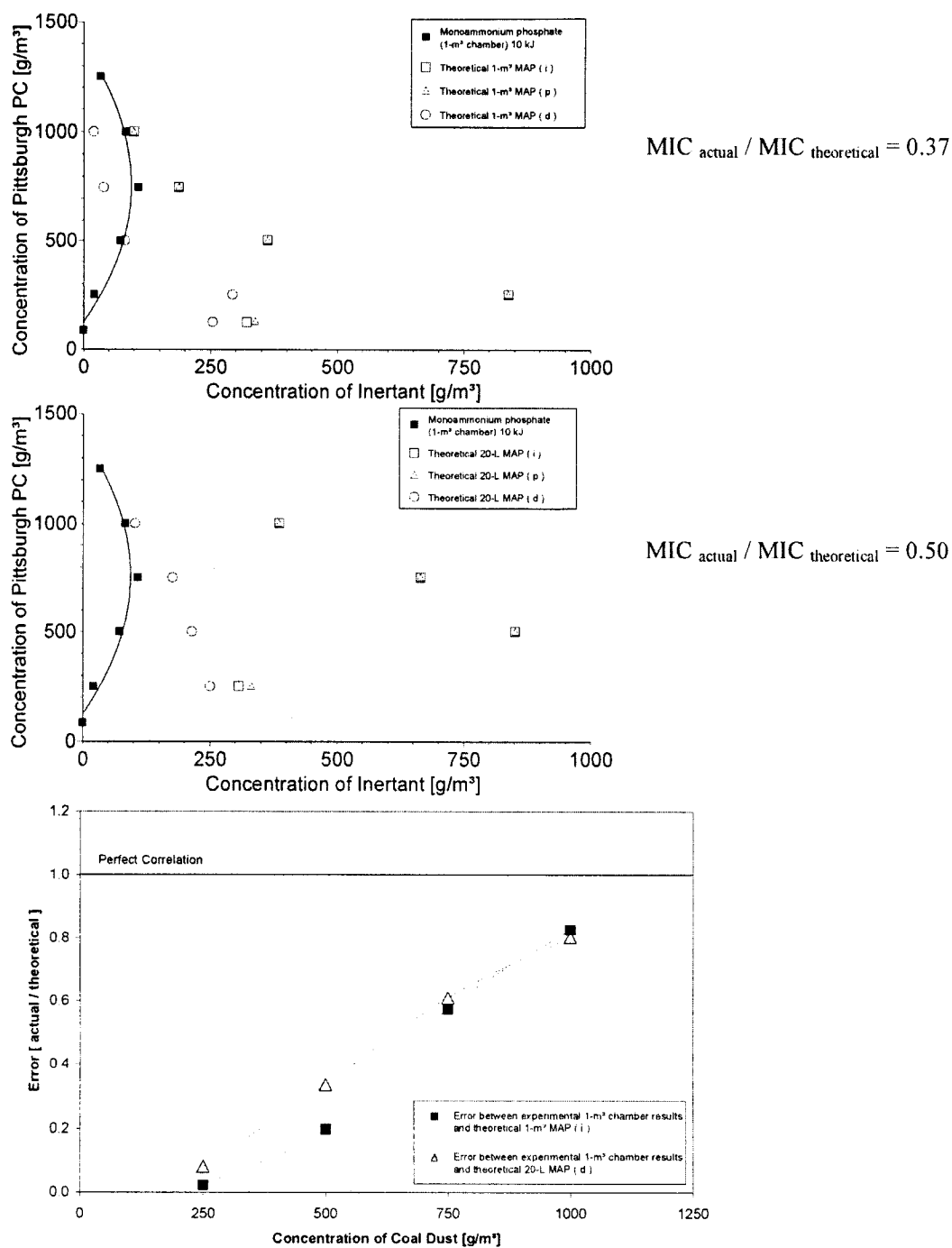


Figure 5.14: Inerting coal dust with monoammonium phosphate.

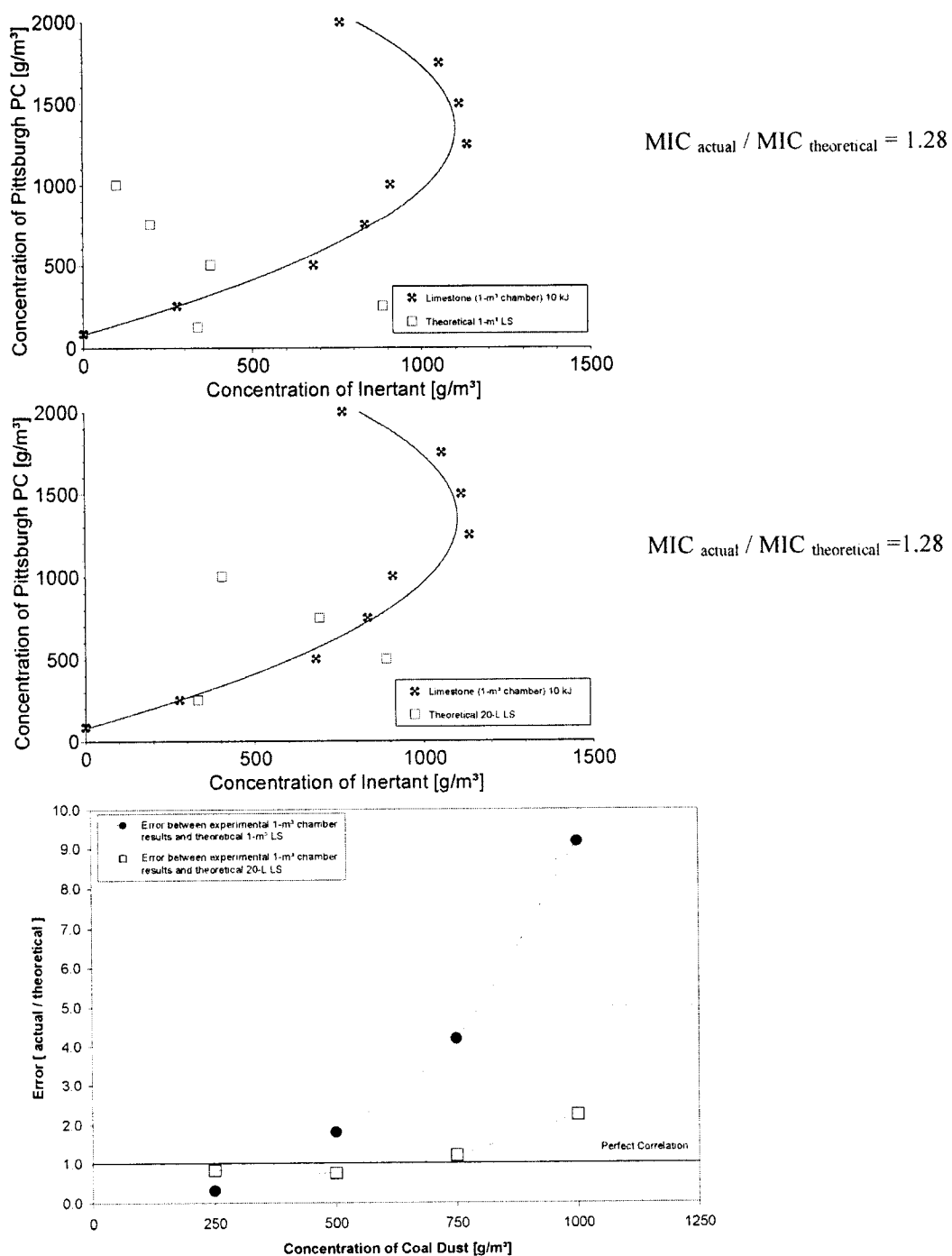


Figure 5.15: Inerting coal dust with limestone.

the explosion. The model does not include any limiting factors that may influence heat transfer, such as the time dependency of thermal conduction. This second issue may be handled by developing a β -Factor for the inertant based on its time-dependent efficiency in heat absorption. The corrected inertant participation level, depending on fuel combustion speed, could then be applied to the model. Such consideration is beyond the scope of the current CAFT model, but could be considered for its further development. This would be a variation of the current attempt to model inertant efficiency by permitting three states of decomposition (nil, partial or complete).

5.7 CONCLUSION

The 20-L and 1-m³ CAFT models have been shown to be useful in predicting the experimentally determined inerting levels from a 1-m³ chamber across a wide variety of fuel types and inertants. The utility of the CAFT model in its current form is as a relative tool to optimize test matrices for experimental determination of minimum inerting concentrations.

Comparison between model and experimental values of inerting levels are generally more favorable at low fuel dust concentrations and for slower burning dusts (i.e. not aluminum). The limitations of the models include the uncertainties inherent in determining the β -Factor for the fuel and model assumptions of efficient heat absorption by the inertant. Additionally, chemical mitigation by the inertant was not considered.

5.8 ACKNOWLEDGMENTS

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6 GENERAL CONCLUSIONS

Presented in Section 1 of this thesis were five questions that were the central focus of this thesis. The five peer-reviewed journal papers presented in Sections 2 to 5 and in Section 8 have answered these questions. The questions are presented here again below:

- 1) “Can inerting envelopes be measured in the 1-m³ chamber for other types of dusts besides coal dust and cornstarch powder?”
- 2) “Will small-scale (20 L) inerting levels match intermediate-scale (1 m³) inerting levels, and under what test conditions will the small-scale and intermediate-scale inerting levels come to agreement?”
- 3) “Can inerting envelopes be measured in the small-scale chamber?”
- 4) “Since it has been demonstrated that small-scale inerting levels agree with mine-scale values, will intermediate-scale inerting levels agree with mine-scale results?”
- 5) “Can a model be developed to act as a predictive/screening tool to assist in inerting level estimation and thereby reduce the number of experiments that need to be performed?”

An inerting envelope and MIC were observed for the mitigation of anthraquinone dust explosibility using sodium bicarbonate in the 1-m³ chamber. This finding parallels the previous observations by the researchers at Fike Corporation for the mitigation of Pittsburgh pulverized coal dust explosions with monoammonium phosphate, sodium bicarbonate and limestone; and cornstarch explosions with monoammonium phosphate and sodium bicarbonate in the 1-m³ chamber.

For all combinations of fuel and inertant used for the experiments presented in Section 2, the relative amount of inertant decreased as fuel concentration increased. However, when the concentration of inertant is expressed in absolute terms as in an inerting envelope, this trend is not readily apparent for all materials tested. No definite inerting envelope was

formed for the mitigation of aluminum dust and polyethylene dust explosions using sodium bicarbonate or monoammonium phosphate as inertants in the 1-m³ chamber. As a result, there were no definitive MIC's formed for these material combinations.

Although the MIC was not observed for these dusts, an effective MIC, as described in Section 2.5, could be used to develop an explosion mitigation strategy. By determining the maximum quantity of dust/powder that may be present in a particular operating unit or environment, a suppression system design could be engineered based on the minimum quantity of inertant required to mitigate an explosion involving this maximum fuel concentration. This engineered system would then also be effective in mitigating lower fuel dust concentrations as well.

From previous work, the 20-L chamber using a 5-kJ ignition source produced coal dust inerting levels using rock dust that matched mine-scale inerting levels. However, in inerting level experiments conducted for the current work, the 20-L chamber using a 5-kJ ignition source did not match the inerting level determined in the 1-m³ volume for the majority of the dust combinations tested. The only exception was aluminum inerting with sodium bicarbonate and monoammonium phosphate. Factors that may have been involved in these inerting results are the finer particle size of the aluminum powder than the carbonaceous dusts tested and the fact that aluminum has a higher flame temperature than the other materials tested.

While inerting envelopes were observed in the 20-L chamber using a 5-kJ ignition source for some fuel dust/ inertant mixtures, specifically cornstarch inerting with sodium bicarbonate and Pittsburgh pulverized coal dust inerting with monoammonium phosphate, definite inerting envelopes of the other materials were not observed. However, the dependence of the inerting level on fuel concentration observed in the 1-m³ vessel was observed, to a lesser extent, in the 20-L chamber. In general, the inerting levels produced in the 20-L Siwek chamber using a 5-kJ ignition source were greater than the inerting levels observed in the 1-m³ using a 10-kJ ignition source.

By using lower energy ignitors for the inerting tests in the 20-L chamber, the resulting inerting levels matched 1-m³ chamber inerting levels more closely. For some

carbonaceous dusts such as cornstarch and Pittsburgh pulverized coal dust, performing explosibility tests using ignition energies of 0.5 to 1 kJ produced inerting envelopes similar to the ones observed in the 1-m³ chamber using a 10-kJ ignitor. It should be noted that the usage of the lower strength ignitors did not influence the inerting levels for all carbonaceous dusts. Inerting of Pittsburgh pulverized coal dust and anthraquinone with sodium bicarbonate using a 1-kJ ignition source in the 20-L chamber greatly reduced the inerting level to match values approximating those observed in the 1-m³ chamber, but no distinct envelopes were formed. This finding permits the use of the 20-L chamber in MIC determination for some materials with careful consideration of test conditions such as ignition energy (see Section 3.5.2).

It should be noted that monoammonium phosphate was a more effective inertant than sodium bicarbonate for carbonaceous dusts. This observation agrees with results from other researchers (Hertzberg et al., 1984 and Amrogowicz and Kordylewski 1991). This trend in effectiveness was observed in both the 20-L chamber and the 1-m³ chamber inerting experiments. It would be reasonable to expect that sodium bicarbonate would have been more effective since it had a smaller particle size and therefore more exposed surface area for heat absorption. Monoammonium phosphate, therefore, must be a better inhibitor due to thermal and chemical considerations.

A very interesting observation was made when comparing the inerting levels determined for coal dust mixed with rock dust in the 1-m³ chamber to the inerting levels determined in the 20-L Siwek chamber. The 1-m³ inerting levels were lower than those found in the 20-L chamber for both mine-size coal and pulverized coal dust (see Sections 4.4 and 8.5.1). This may be caused by too strong an ignition energy overdriving the smaller chamber. Agreement between the 20-L chamber (using a 5-kJ ignition source) and mine-scale inerting levels may have been due to overdriving of the smaller chamber reproducing the effects of flame acceleration on mine-scale results. It is possible that test conditions for inerting level determination have to be modified depending on the scale to which the results will be extrapolated. This may imply the use of relatively weak ignition sources for geometries with low L/D ratios and high ignition energies for geometries with high L/D ratios.

This observation adds to the versatility in the usage of the 20-L Siwek chamber in establishing dust explosion inerting levels. By modifying the ignition source strength for a given set of experiments, the inerting test results can be applied to high L/D ratio mine-scale environments (strong ignition source) or low L/D ratio intermediate-scale process unit environments (weak ignition source). Additionally, testing economies of time and quantity of test dust/powder are realized by using the smaller 20-L scale. This observation would only apply to inerting level determination and not to vent sizing experiments. Vent sizing experiments conducted in the 20-L volume would still require a 10-kJ ignition source to produce acceptable results.

Further economies for experimentally determined inerting levels could be realized by using the CAFT model presented in this thesis. The 20-L and 1-m³ CAFT models have been shown to be useful in predicting the experimentally determined inerting levels from a 1-m³ chamber across a wide variety of fuel types and inertants. The utility of the CAFT model in its current form is as a relative tool to optimize test matrices for experimental determination of minimum inerting concentrations.

Comparisons between model and experimental values of inerting levels are generally more favorable at low fuel dust concentrations and for slower burning dusts (i.e. not aluminum). The limitations of the models include the uncertainties inherent in determining the β -Factor for the fuel and model assumptions of efficient heat absorption by the inertant. Additionally, chemical mitigation by the inertant was not considered.

This work presented in this thesis has answered all five questions posed in Section 1. It has demonstrated that the MIC phenomenon observed with cornstarch and Pittsburgh pulverized coal dust was also present for another carbonaceous dust (anthraquinone). It has established that the MIC can be observed in both the 1-m³ and the 20-L volume. It has verified the versatility of the 20-L chamber and its utility in determining scalable inerting levels by varying the ignition source strength used for testing. It has demonstrated that inerting levels determined in the 1-m³ chamber may not scale up to high L/D ratio environments such as a mine gallery. Finally, it has provided a computer

model which can be used as an aid, and predictive tool, for inerting level determination in both the small-scale and intermediate-scale vessels.

7 FURTHER WORK

It is recommended that the following issues be investigated in future work:

- 1) Inerting levels at the intermediate-scale using various L/D ratios should be examined. Over a moderate range of L/D ratios observations could be made as to whether flame acceleration down the length of the vessel may result in higher inerting levels. These levels may be in better agreement with mine-scale and 5-kJ-ignition-source 20-L vessel inerting levels. Caution should be exercised since using too large an L/D ratio, while keeping the intermediate volume at 1 m^3 , may result in wall quenching of the flame front and produce lower inerting levels.
- 2) The test setup for the 1-m^3 vessel used for the inerting level experiments may not have sufficient turbulence for inerting level experiments requiring large quantities of fuel and inert powder. The current setup may be sufficient for P_{\max} and K_{St} tests which usually require lower quantities of material. Charging the dispersion reservoirs with more pressure, and evacuating the test vessel to lower pressures, in conjunction with a shorter ignition delay time may significantly increase the level of turbulence in the 1-m^3 chamber. Inerting levels determined under these conditions may match those produced at mine and smaller scales.
- 3) Development of the beta factor for a specific fuel using a series of mono-size particles could be used to ascertain if the beta factor is influenced by particle size. Assessment of the suitability of the model to better fit smaller size fuel particles than larger ones can be made. It is possible that the smaller size particles will more readily volatilize, thus increasing their participation in the combustion process.
- 4) Determination of the influence of dP/dt on the beta factor is also important. This could be investigated for several materials or one material with a series of discrete particle sizes. Questions as to whether the model works better for slow-burning particles than fast-burning particles can be answered. Changing the ignition delay time to reduce turbulence would affect dP/dt . If the series of mono-sized particles are

used, cross correlation of the particle size influence and the dP/dt influence on the experimental and model predicted inerting levels can be established.

- 5) Development of a beta factor for the inertant should also be examined. It is possible that the whole mass of the inertant does not act as a thermal sink. Additionally, inertant particle size effects on the inertant beta factor can be determined. Furthermore, the effect of the fuel dP/dt on the inertant beta factor can be established. Faster burning fuels (greater dP/dt) may result in a smaller inerting participation of the heat sink.
- 6) The beta factor in the current model is used to modify the volatile component of the fuel to match the explosion pressures observed experimentally in the 20-L chamber and the 1-m³ chambers. This method therefore attempts to account for the nonadiabatic nature of combustion in each chamber as well as compensate for incomplete volatile-material release (or nonparticipation in combustion) during the finite combustion reaction time. A fixed vessel-independent limit flame temperature is then used as the criterion for flame propagation prediction by the model.

An alternative approach would be to use the beta factor solely to compensate for incomplete volatile material release (or nonparticipation in combustion). In this method the beta factor would be 1 until the stoichiometric volatile-air mixture ratio is achieved. It would then decrease so as to keep the volatile component of the solid fuel at the stoichiometric volatile-air ratio. The beta factor would then approach 0 as solid fuel concentration is increased. Under this alternative method however the nonadiabatic nature of combustion and the influence of test vessel size would have to be accounted for by modifying the limit flame temperature for each test chamber and ignition energy used. This means that the series of limit flame temperatures will be obtained by MEC determination in each chamber using various ignition energies. This alternative method may be simpler to implement since it is less computationally intensive than the current method discussed in this thesis.

Both methods are approximations of the actual physics of the combustion process in each test chamber. The current method has been demonstrated to work to a limited

degree in predicting the inerting level in both the 20-L and 1-m³ chambers. As possible future work, the model may be modified to conform to the alternative modeling approach described above. The inerting results produced can then be compared between the two methods and their merits as predictive/screening tools evaluated.

- 7) Ideally an a priori theoretical study should be conducted of the conditions in a thin layer at the flame front just at the point of quenching (i.e. when the devolatilization of the dust particles plus the rate of reaction of the gases is equal to the rate of absorption of heat by the inerts) - thus creating a kinetic model for inerting without using adjustable parameters. Initially a "zero turbulence" model should be developed followed by a model including turbulence.

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9 APPENDIX A - SCALING OF DUST EXPLOSION INERTING

This section was originally presented as "*Scaling of dust explosion inerting*" at the Eight International Colloquium on Dust Explosions, Schaumburg, Illinois, September 21 – 25, 1998. The authors were A. G. Dastidar, P. R. Amyotte, J. Going and K. Chatrathi.

The conference paper was later published as:

A. G. Dastidar, P. R. Amyotte, J. Going and K. Chatrathi, "*Scaling of dust explosion inerting*", **Archivum Combustionis**, vol. 18, no. 1 – 4, 1998*. The text and figures in this section are identical to that of the published paper with the exception that section numbers have been added, and figure and table numbers have been changed, to reflect the thesis format.

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9.1 ABSTRACT

Experiments were performed to compare intermediate-scale (1-m^3) and laboratory-scale (20-L) inerting results. Intermediate-scale inerting levels appear to be lower than laboratory-scale values. This can possibly be attributed to the use of a strong ignition source to initiate the test, which may have overdriven the explosions in the smaller test vessel. Previously reported agreement between the smaller test vessel and full-scale experiments may be due to overdriving in the 20-L chamber, leading to high inerting levels similar to those encountered in full-scale tests due to flame acceleration.

A new flammability limit parameter has been defined as the Minimum Inerting Concentration (MIC; in units of mass concentration, i.e. g/m^3). This is the concentration of inertant required to prevent a dust explosion regardless of fuel concentration. Previous experimental work at Fike in a 1-m^3 spherical chamber has shown this flammability limit to exist for pulverized coal dust and cornstarch. In the current work, inerting experiments with aluminum, anthraquinone and polyethylene dusts as fuels were performed in a 1-m^3 chamber, using monoammonium phosphate and sodium bicarbonate as inertants. The results show that an MIC exists only for anthraquinone inerted with sodium bicarbonate. Preliminary tests with anthraquinone and sodium bicarbonate in a 20-L Siwek chamber using a strong ignition source do not show a similar trend. This may be due to overdriving.

In the 1-m^3 tests, the other combustible dust and inertant mixtures did not show a definitive MIC, although they did show a strong dependence between inerting level and suspended fuel concentration. As the fuel concentration increased, the amount of inertant required to prevent an explosion decreased. Even though a definitive MIC was not found for most of the dusts, an effective MIC can be estimated from the data. The use of MIC data can aid in the design of explosion suppression schemes.

9.2 INTRODUCTION

Dust explosions are a serious hazard in the process industries. Suppressants are widely used to provide protection against such explosions. For suppression to be effective, it is important to determine the amount of inertant required to prevent an explosion of the dust at any concentration. Inerting concentrations can be determined by performing suppression tests with laboratory-scale equipment or with large- or full-scale equipment. Laboratory-scale tests are often done due to the cost and effort required for full-scale testing.

An additional flammability limit parameter is defined for inerting dust clouds with particulate material. This new parameter is called the Minimum Inerting Concentration (MIC; in units of mass concentration, i.e. g/m³). Minimum inerting concentration is the lowest inert dust concentration above which a dust explosion is not possible for any fuel concentration. The MIC can be determined by measuring the full flammability curve for the fuel-air-inert dust mixture. The approach differs from suppression testing in that the fuel and inertant are pre-mixed and collectively injected into the test vessel.

Experiments have been conducted using the Fike 1-m³ spherical chamber with three different dusts: aluminum, anthraquinone, and polyethylene. The inertants used were monoammonium phosphate and sodium bicarbonate, which have been shown to be effective explosion suppressants (Dastidar *et al.* (1998a)). By performing dust explosibility tests using premixed quantities of fuel and inertant, an inerting envelope can be determined.

The use of the MIC in the design of explosion suppression systems for industrial equipment and chemical isolation barriers in pipes is important. Suppression and isolation designs having inert agent concentrations below the MIC will have the possibility of allowing dust explosions to occur. Therefore, the MIC provides guidance for the safe design of suppression and chemical barrier systems.

It would be economically advantageous to perform MIC tests in smaller explosion vessels. A key parameter in inerting and suppression testing is the vessel volume. Too

small a vessel will not allow for proper flame front development and may underestimate the inerting requirement. A related parameter is the ignition energy. An ignition source that is too large may lead to overdriving the explosion and overestimating the inertant requirement.

9.3 BACKGROUND

The ignition sequence of a dust cloud due to a spark ignition source described by van Larr and Zeeuwen (1985) can also be used for pyrotechnic ignition. The authors state that spark breakdown (discharge of the ignitor) results in the ignition of an initial dust/air kernel. This only occurs if the ignition source produces enough energy to heat up the dust/air kernel to its ignition temperature, and if the heat release rate from the ignition source is as fast as the heat absorption rate of the kernel. If the energy is insufficient in magnitude or delivery rate, the kernel will not ignite. Once ignited, this kernel then acts as the ignition source for the dust surrounding it. If the primary kernel can produce sufficient energy fast enough, it will then ignite the dust surrounding it (producing a secondary kernel) and flame propagation will continue. If the primary kernel cannot produce sufficient energy fast enough, the flame front is extinguished.

The role of an inertant, such as limestone, is to absorb the energy from the ignition source or the primary kernel so that flame propagation cannot occur. Hertzberg *et al.* (1984) argue that inertants can act "thermally" and "chemically". A "thermal" inertant is one that absorbs heat energy from the flame and prevents propagation. Also if devolatilization of the inertant occurs, inerting can be accomplished by diluting the concentration of gaseous fuel in the combustion zone below the lower flammability limit. A "chemical" inertant, the authors explain, is one that devolatilizes in the flame zone, with the gases given off inhibiting flame propagation. These gases inert the combustion process by acting as a chain terminator of kinetic mechanisms. The key to inerting appears to be the relative rates at which particle devolatilization occurs (both fuel and inertant).

In industrial situations the ignition sources of dust explosions can vary from relatively weak electrostatic discharges to strong open flames. The energy given off by these sources can vary. For experimental purposes, pyrotechnic ignition sources are used. If the

ignition source is too large the inertant may not be able to prevent ignition of the primary kernel, but can prevent ignition of the secondary kernel. A strong ignitor could produce a large primary kernel. As a result, combustion of the dust within this larger kernel can cause a significant pressure rise in a 20-L vessel but have a negligible effect on the pressure in a 1-m³ chamber. This phenomenon is known as overdriving.

Overdriving of the explosion occurs when the ignition source (and as a result the flame produced by the ignition source) is large compared to the vessel volume. This has two consequences; it changes the initial test conditions of the dust cloud (increasing the temperature), thereby possibly making a nonexplosible dust explosible. It can also result in burning of the dust within the ignitor flame, but with no real propagation beyond the ignition source. Since the ignition source volume is very large compared to the vessel volume, the dust appears to explode and as a result the overpressure and rate of pressure rise are overestimated.

Work by Cashdollar and Chatrathi (1992) and Cashdollar *et al.* (1992) has shown that anthracite tested in a 20-L chamber using a 5-kJ ignition source was explosible. However, in a 1-m³ vessel even a very strong 30-kJ ignition source did not produce an explosion. Also, they determined the minimum explosible concentration (MEC) for Pittsburgh coal (37% volatiles) and gilsonite (84% volatiles) at different ignition energies. The 20-L chamber showed evidence of overdriving because it produced MEC levels lower than the 1-m³ chamber. An interesting observation that can be made is that the MEC of gilsonite did not change as significantly as the MEC of Pittsburgh coal as ignition energy was increased. This may be due to the higher volatile content of gilsonite. Sufficient volatile matter may have been released from gilsonite quickly enough to produce a flammable mixture of fuel and air to take part in the combustion process before the flame front was quenched by the wall. For Pittsburgh coal, the higher ignition energies were able to release greater amounts of volatile matter from the dust. This volatile matter was enough to form flammable concentrations from smaller quantities of dust, leading to lower MEC's.

Zhen and Leuckel (1997) have also commented on the importance of ignition energy. They have stated that a volumetric/multipoint ignition source such as a Sobbe pyrotechnic ignitor has a limited effect on the explosion parameters in a 1-m³ vessel. Dust explosion experiments performed using a 10-kJ and 75-J ignition source produced nearly the same overpressure but different rates of pressure rise for cornstarch. The ignitor volume in a 1-m³ vessel may be considered to be relatively small compared to the chamber volume; therefore there exists a reduced sensitivity of explosion overpressure to ignition energy. The authors comment, however, that in smaller chambers the volumetric/multipoint nature of the ignition source is of greater importance because it produces a relatively larger ignition kernel (a 5-kJ ignitor can produce a flame that is about 35% the size of a 20-L chamber). This large flame may have a stronger influence on the explosion parameters.

Another key phenomenon for dust explosion scaling is quenching of combustion by the vessel walls. Smaller spheres have a larger surface area to volume ratio; as a result the expanding flame reaches the vessel wall quickly and is cooled by the thermal mass of the wall. Siwek (1980) has shown that overpressures observed in a 1-m³ chamber are slightly higher than overpressures observed in the 20-L Siwek chamber for material with high P_{\max} values. A similar conclusion was arrived at by Kumar *et al.* (1992) who performed tests in a 10.3-m³ silo with an L/D ratio of 3.8. They found overpressures determined in their silo to be slightly higher than those observed in smaller vessels. The vessel geometry may play a major role in interpreting this work. Flame propagation in a silo is very different than flame propagation in a spherical chamber. This difference, not wall quenching of the flame, may account for the observations made by Kumar *et al.* (1992).

There may be no limit to the phenomenon of quenching due to scale. This is illustrated by work done by the US Bureau of Mines (USBM) at the Lake Lynn Experimental Mine (LLEM) and the older Bruceton Experimental Mine (BEM), which has a smaller cross sectional area than the LLEM (Cashdollar *et al.* (1992); Cashdollar (1996)). Coal dust explosions performed in the LLEM required more rock dust to inert than experiments in the BEM using coals of similar volatility. The researchers attributed this difference to quenching of the flame by the walls in the smaller mine. It is important to note that this

difference was greater for coals of lower volatility than it was for coals of higher volatility.

Dastidar *et al.* (1997) have shown that experimental inerting data from a 20-L Siwek chamber are in good agreement with inerting results obtained from the USBM LLEM. Mine-scale inerting levels of Pittsburgh and Pocahontas pulverized coals were reported to be 79% and >68%, respectively; inerting results from the smaller chamber were 78% for Pittsburgh pulverized coal and 74% for Pocahontas pulverized coal using a 5-kJ ignition source. This relatively good agreement between large- and small-scale inerting results prompted the current interest in comparing small-scale inerting results with intermediate-scale experiments (1-m³ chamber).

Dahoe *et al.* (1996) discuss propagation of a dust explosion in a spherical vessel in terms of a multi-zone model. In this model there are three distinct regions of a burning dust cloud. If combustion of a dust cloud were to occur from the centre and propagate outward, this would produce a burned region in the centre, a propagating flame zone of finite thickness, and an outer zone of unburned material. Previous models considered the flame zone to be infinitely thin, in which case there would be little difference between flame propagation in a 1-m³ chamber and a 20-L chamber. Dahoe *et al.* (1996) theorized that the flame zone had a definite thickness which is dependent on the type of material being burned.

As the burning velocity or burning time changes with different dusts, the flame zone thickness would change. The authors theorize that in a 1-m³ vessel the flame zone would be thinner than the radius of the combustion chamber and that true propagation would occur. In a smaller 20-L chamber, the flame zone thickness may be equal to or greater than the vessel radius. This may have a quenching effect on the dust explosion. This is evident from their model where K_{St} decreases as vessel volume decreases for a given flame thickness. It appears that as flame thickness decreases, the quenching effect is diminished.

Previous work by Dastidar *et al.* (1997) has shown that there is a strong inter-dependence of the relative amount of premixed inertant required to prevent an explosion and the fuel

concentration. The authors report from tests of Pittsburgh and Pocahontas pulverized coals that fuel concentrations near stoichiometric volatile-air mixtures required more limestone to prevent an explosion than higher fuel concentrations. These stoichiometric volatile-air mixtures represent the fuel concentration that produces the maximum explosion overpressure. At volatile-air ratios in excess of stoichiometric there is insufficient oxygen for complete combustion, and the unreacted material acts as a thermal sink, helping to inert the explosion. As a result, a decrease in overpressure is observed. For inerting work this implies that at high fuel concentrations the excess fuel dust acts to increase the effective thermal sink in the dust mixture. Since the fuel aids the inertant there is less inertant needed to prevent an explosion.

The same point was argued by Mintz (1993): by increasing the concentration of fuel in a fixed volume chamber, a very dense dust cloud is formed. In such a cloud, when a fuel particle burns, all the oxygen in its immediate vicinity is consumed in the reaction zone. This, however, will also consume the oxygen that would be required by the neighboring fuel particle for combustion. The transient nature of the combustion propagation wave also means that there is insufficient time for oxygen to be transported to the particle in a dense dust cloud. This implies that even though there may be sufficient oxygen for combustion globally, there is not enough oxygen in the local vicinity. As a result, the neighboring particle does not burn. This unburned particle then acts as a heat sink reducing the flame temperature and the explosion overpressure. By adding an inertant to the dust mixture, a very dense dust cloud is formed at low fuel concentrations thereby hindering the transport of oxygen to the fuel particle in time for combustion to occur, as well as acting as a thermal sink.

Inerting experiments at Fike have shown a similar concentration dependence on explosion inerting. By plotting the data as fuel and inertant concentrations, the results form an inerting envelope very similar to a flammability envelope. Figures 9.1 and 9.2 show the inerting envelope for Pittsburgh pulverized coal and cornstarch, respectively. The data points represent the explosibility limit of the fuel-inertant mixture. The data points are interpolated by averaging the highest inertant concentration tested that

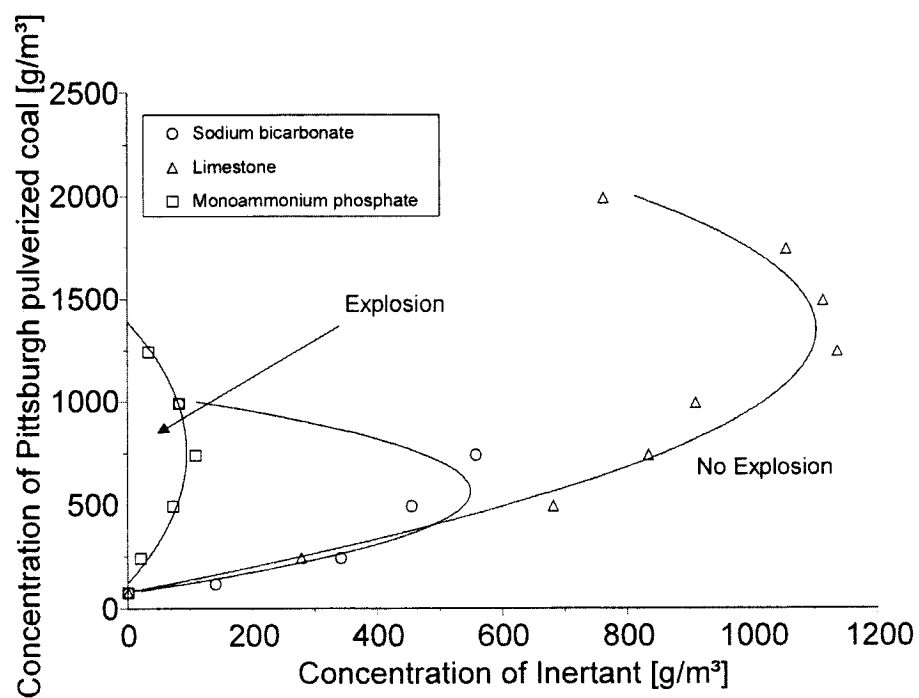


Figure 9.1: Inerting envelope for Pittsburgh pulverized coal dust with sodium bicarbonate, monoammonium phosphate and limestone as inertants. Experiments conducted in a spherical 1- m^3 chamber using two 5-kJ ignitors as an ignition source.

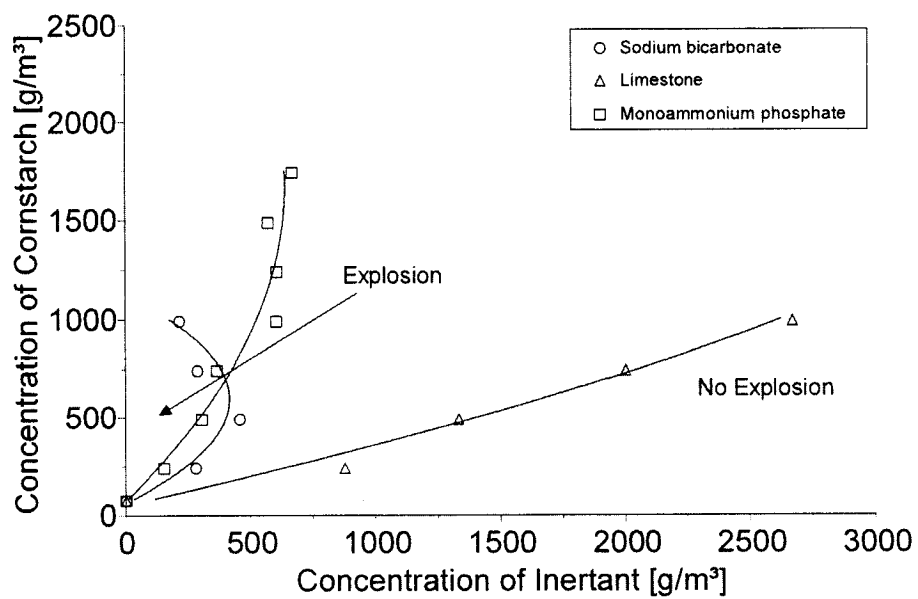


Figure 9.2: Inerting envelope for cornstarch dust with sodium bicarbonate, monoammonium phosphate and limestone as inertants. Experiments conducted in a spherical 1-m³ chamber using two 5-kJ ignitors as an ignition source.

produced an explosion with the lowest inertant concentration tested that did not produce an explosion for a given fuel concentration. The area to the left of the curve represents the explosible area. In this area there is insufficient inertant to prevent an explosion. The area to the right of the curve represents the nonexplosible area; here there is sufficient inertant to prevent an explosion. The “nose” of the envelope represents the least amount of inertant that would prevent an explosion regardless of fuel concentration.

If this trend is observed for other dusts it could be a useful tool from which adequate protection measures can be implemented. Since at any given time it is very difficult to determine the actual suspended dust concentration in process equipment, or even the potential suspended dust concentration from a process upset, estimates are made in designing explosion protection equipment. One of these estimates is to take the worst case scenario and perform inerting experiments at the fuel concentration that produces the highest overpressure. This results in a relative amount of inertant required to prevent an explosion. The inerting level cannot be used as an absolute concentration of inertant because higher fuel concentrations would require greater amounts of inert material to prevent an explosion (even though the relative concentration may be less). If the inerting level was to be maintained as a constant ratio, large quantities of inertant would be required at high fuel concentrations. While this may guaranty safety, it poses certain equipment design problems. Suppression devices have to be very large and complicated to be able to introduce such large quantities into the process unit, and the process units themselves have to be designed to accommodate these larger suppression devices.

If, however, an MIC were to exist for a dust, suppression strategies could be designed to introduce a fixed concentration of inertant. A fixed number of high rate discharge containers could be attached to a process unit giving a fixed concentration of inertant. At both low and high fuel concentrations there would be enough inertant to prevent an explosion. So if the concentration of explosible dust were to increase or decrease in the unit, there would always be sufficient inertant to suppress an explosion.

A key point which must be made is that the MIC is an ignition limit, not a suppression limit. This is due to the fact that the inert matter is premixed with the fuel when injected

into the test vessel. This intimate contact between the fuel and inertant represents an ideal case. For suppression there may be losses in inertant effectiveness due to the type of dispersion from the discharge canister and incomplete mixing between the inertant and the fuel.

Siwek (1980) showed that, for the same dust, the 20-L chamber generates slightly lower overpressures than a 1-m³ vessel, and that the difference increases with higher overpressures. This fact could limit the applicability of inerting levels determined in the 20-L Siwek chamber. The objective of this study therefore is to determine the inerting level of several dusts in both a 20-L Siwek chamber and a 1-m³ vessel (in terms of both the “relative” inerting level reported as %, and also the “absolute” MIC inerting envelope, reported as g/m³). This will illustrate the comparability of inerting levels in these vessels and demonstrate the most appropriate ignition energy to be used for 20-L inerting experiments.

9.4 EXPERIMENTAL

To compare the influence of scale on the inerting level of dust explosions, experiments were performed in two different vessels: the Fike 1-m³ vessel and the 20-L Siwek explosion chamber. The Fike 1-m³ vessel is a spherical explosion chamber designed to gather explosion severity and explosion protection testing data. A schematic of the apparatus is shown in Figure 9.3. For inerting tests, both combustible dust and inert solid are premixed and then introduced into the vessel. The vessel is made of two 122-cm internal diameter, 0.95-cm thick carbon steel hemispherical sections that can be separated to allow access to the interior. These two halves of the sphere are connected by twelve 51-mm diameter bolts. The vessel has a design pressure of 21 bar (g).

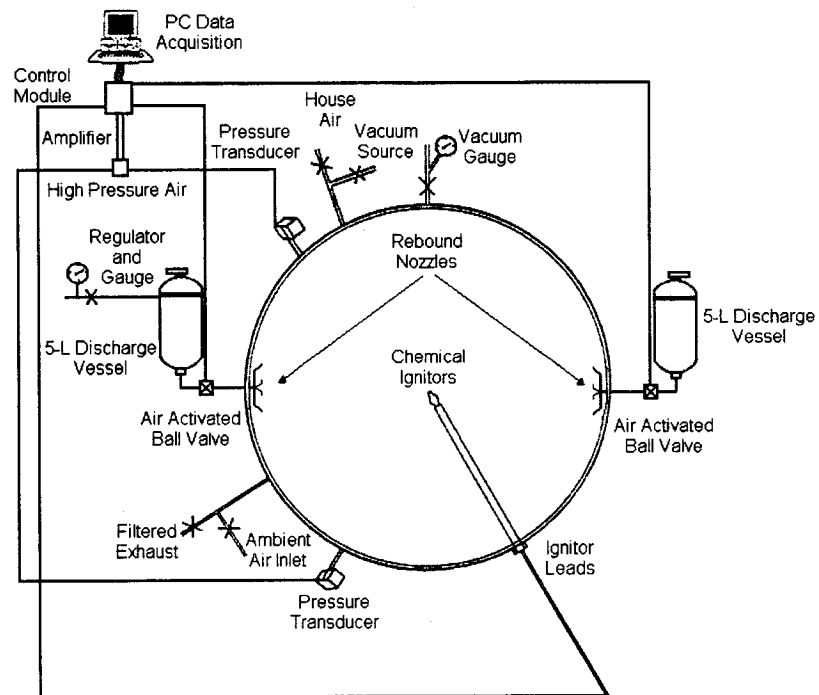


Figure 9.3: Fike 1-m³ vessel.

The dust injection system consists of two 5-L discharge cylinders, each with a ball valve and a Kühner type rebound nozzle for dust dispersion. The outlets on the discharge cylinders and ball valves are 19 mm in diameter. To create a combustible dust cloud in the 1-m³ chamber, a weighed amount of premixed dust and inertant mixture is placed equally into both 5-L cylinders. The 5-L discharge cylinders are pressurized to 19.3 bar(g) each, and the 1-m³ vessel is partially evacuated to 0.88 bar for the dust explosion to occur at atmospheric pressure. The ball valves between the discharge cylinders and the rebound nozzles are opened by using a pneumatic actuator. The air and the dust in the discharge cylinder enter the 1-m³ vessel through the rebound nozzles to create the dust cloud.

The dust explosions are initiated with two chemical ignitors triggered 0.7 s after the activation of the ball valve. The chemical ignitors are manufactured by Sobbe and contain 40% zirconium, 30% barium nitrate and 30% barium peroxide. Each ignitor has 1.2 grams of this mixture and has a stored energy of 5 kJ. The energy is released in about 10 ms. The discharge of a single 5-kJ ignitor by itself will cause the pressure to rise by 11 mbar in the 1-m³ chamber.

Two variable reluctance pressure transducers manufactured by Validyne (model DP 215) are used to monitor the progress of the explosions. The transducers in combination with their amplifier electronics have a sufficiently fast response time to provide pressure measurements with a 1 ms resolution. A Metrabyte data acquisition board is used in conjunction with a personal computer to gather the pressure data as a function of time and to control the experiments. Two D/A channels on the data acquisition board are used to activate the ball valves and to initiate the chemical ignitors. Software programming allows control of the delay time between activation of the valves and ignition. It also allows the conversion of the analogue signals into absolute pressure measurements.

Previously, the 1-m³ chamber had only one discharge chamber and dispersion ring. The dispersion time and turbulence level were comparable to those in the European 1-m³ chambers (Bartknecht (1989)). This is the turbulence level in ASTM Standard E1226, ISO Standard 6184/1, NFPA Guide 68, and VDI Standard 3673 to determine the

maximum rate of pressure rise to determine vent sizes. However, since the nature of inerting experiments requires greater quantities of material (dust and inertant) to be injected into the explosion chamber, the apparatus has been modified to use two dispersion chambers. The ignition delay time has been increased from 0.55 s to 0.7 s and the discharge chamber pressurization has been decreased from 32 bar(g) to 19.3 bar(g) to maintain similar turbulence levels. This procedure is recommended by Bartknecht (1989).

Two sets of 1-m³ experiments were performed. The first experimental set was conducted using mine-size coal dust and rock dust. A sample of coal from the Prince mine was obtained from the Cape Breton Development Corporation (CBDC). At DalTech, the coal was ground and sieved to produce a coarse fraction having a broad particle size distribution (CBDC mine-size coal); the volume mean particle diameter determined by sieve analysis was 348 μm . A proximate analysis was performed on the coal sample to determine its composition. The coal consisted of 33% fixed carbon, 37% volatile matter, 27% ash and 3% moisture. A sample of dolomite (rock dust) was received from CBDC to be used as the inertant; its volume mean particle diameter determined using a Malvern Instruments 2600 Series analyzer was 50 μm .

To determine the inerting level of this mine-size coal dust, experiments were conducted using a fixed concentration of fuel dust and varying the relative concentration of dolomite. The overpressure and rate of pressure rise of the explosions were determined from the recorded pressure time traces. Inertant was added to the mixture until the measured overpressure was below the generally accepted 2 bar(a) explosion criterion. The inerting level was determined using ignition energies of 2.5, 5, 10, and 30 kJ, for 500 g/m³ of fuel. Ignition energies of 5 and 10 kJ were used for 1000 g/m³ of fuel.

The dusts used in the second set of 1-m³ experiments (Minimum Inerting Concentration tests) were aluminum, anthraquinone and polyethylene as fuels, and monoammonium phosphate and sodium bicarbonate as inertants. The choice of fuels was made to represent materials commonly used in the process industries: a metal dust, a chemical intermediate for an organic dye and a typical polymer. The inertants, monoammonium phosphate and

sodium bicarbonate, are commonly used suppressants in the explosion protection industry. The particle sizes of the dusts are given in Table 9.1.

Table 9.1: Particle sizes of fuel and inertant dusts used for MIC testing.

Dust	< 100 μm [wt%]	< 25 μm [wt%]	Volume Mean Diameter D_w [μm]
Aluminum	90	50	17
Anthraquinone	92	32	46
Polyethylene	83	17	64
Monoammonium Phosphate	83	18	62
Sodium Bicarbonate	97	32	37

The explosion parameters (overpressure and rate of pressure rise) of the pure fuel dusts were determined as a function of concentration. This was achieved by varying the amount of dust placed in the 5-L discharge chambers. The effect of inertant was then determined for each fuel concentration by measuring the explosion parameters as inertant was added to the mixture. The mixture of inertant and fuel was then placed into the two discharge chambers in equal quantities. The criterion used for an explosion was an overpressure of 2 bar(a).

To determine the influence of scale on the inerting level, both sets of experiments were also performed in a 20-L Siwek chamber. A schematic diagram of the chamber and auxiliary equipment is shown in Figure 9.4. The spherical test chamber has a volume of 20 L and is made of stainless steel with a maximum allowable working pressure of 20 bar. The vessel is surrounded by a water jacket which is used to control the initial temperature of the test chamber. The top access cover is fitted with ignition leads. Sobbe chemical ignitors, similar to those used in the 1-m³ chamber, are connected to the ignition leads. (Different ignitors are used for different ignition energies.)

The desired amounts of fuel dust and inert dust for a given experiment are mixed and placed into the dust storage chamber (volume of 0.6 L). The ignitors are attached to the ignition leads and the test chamber is sealed and partially evacuated to 0.4 bar(a). The computer control program is then initiated and the dust storage chamber pressurized to 20 bar(g) with extra dry compressed air. The computer then opens the solenoid valve

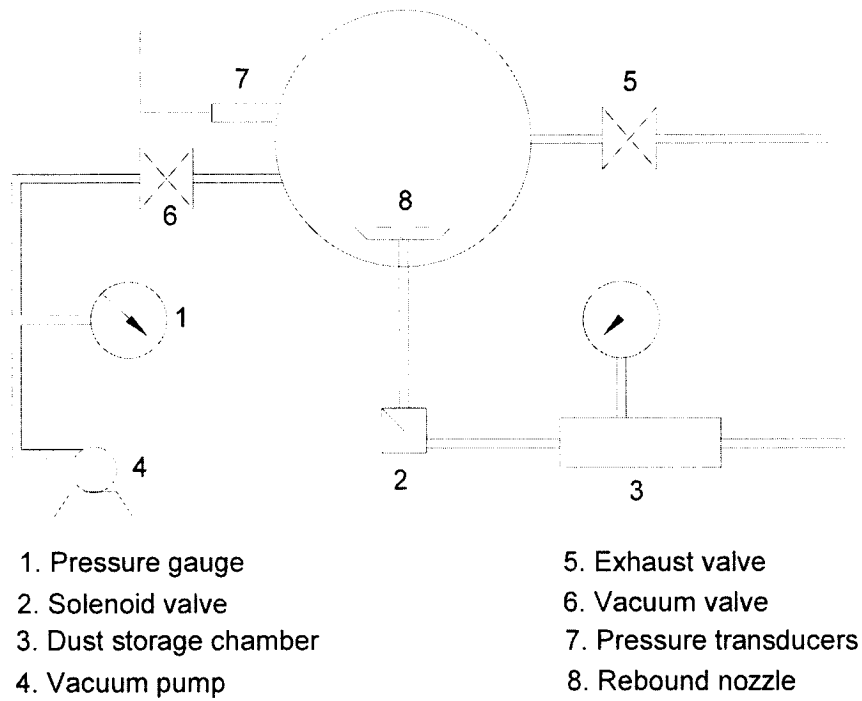


Figure 9.4: 20-L Siwek chamber.

between the dust storage chamber and the test chamber, dispersing the air and dust mixture into the test chamber through a Kühner rebound nozzle and raising the chamber pressure from 0.4 bar(a) to 1 bar(a).

The computer then energizes the ignition source after a time delay of 60 ms. The computer records the pressure-time history of the explosion using two piezoelectric transducers installed flush with the interior of the chamber. The pressure-time trace provides the maximum overpressure (P_{ex}), the maximum overpressure due to the explosion of the dust mixture (P_m) using a correction algorithm to compensate for the pressure increase from the ignitor, and the maximum rate of pressure rise ($(dP/dt)_m$) for a given test. A P_m value of 1 bar(g) (2 bar (a)) was used as the explosion criterion to delineate a non-explosion from an explosion.

The inerting level of mine-size coal dust was determined in a manner similar to that in the 1-m³ chamber; however, ignition energies of 1, 5 and 10 kJ, were used for 500 g/m³ of fuel. An ignition energy of 5 kJ was used for 1000 g/m³ of fuel. Minimum Inerting Concentration tests in the 20-L chamber used anthraquinone as a fuel, and monoammonium phosphate and sodium bicarbonate as inertants (5-kJ ignition source).

Repeat testing was performed, when warranted, for experiments with the lowest inertant concentration that did not produce an explosion for a given fuel concentration. Repeat testing may be limited in this manner due to the relatively higher level of repeatability in the 1-m³ chamber than in the 20-L chamber, and since the objective of this work is to establish a general trend in the inerting level as a function of either ignition energy or inertant concentration.

9.5 RESULTS AND DISCUSSION

9.5.1 Coal Dust Inerting Results

Ideally it would have been favorable to compare mine-size coal dust inerting work conducted in the 1-m³ chamber with that previously done in the 20-L chamber (Dastidar *et al.* (1997)). However, there was insufficient prepared material remaining for 1-m³ testing. Therefore, a new sample of coal was obtained from CBDC. Proximate analysis of

the sample indicated that the coal was unwashed and had a higher ash content of 27%. (The previous sample from Dastidar *et al.* (1997) had 3.7% ash.) Therefore, inerting level testing was performed on the new sample of coal in the 20-L Siwek chamber and compared to previously published results. Figure 9.5 gives this comparison in the form of a plot of total incombustible content (TIC: rock dust, coal moisture and coal ash) as a function of ignition energy. TIC was used to compensate for the differences in ash content of the two coals (previous work and current work). The solid squares represent previously published data (Dastidar *et al.* (1997)) and the hollow circles represent the current work. As can be seen, the inerting results for these two different samples are similar when expressed in terms of TIC. Because of this similarity, the “new” coal sample was deemed suitable for testing in the 1-m³ chamber to compare laboratory-scale inerting levels with an intermediate-scale vessel.

Figure 9.6 compares the inerting level of CBDC mine-size coal dust in the 1-m³ chamber to that of the 20-L Siwek chamber. The inerting levels determined in the 1-m³ chamber are lower than those observed in the 20-L chamber for all ignition energies. In the 1-m³ chamber there is a significant difference in the inerting level between a 2.5-kJ ignition source and a 5-kJ ignition source. However, there was little change in the inerting level as the ignition energy was increased further. A doubling of the ignition energy from 5 kJ to 10 kJ did not produce a significant increase in inerting level: both energies resulted in an inerting level of 34% rock dust. A six-fold increase in ignition energy from 5 kJ to 30 kJ resulted in an increase of the inerting level from 34% to 39% rock dust. Tests were also conducted at a higher fuel concentration of 1000 g/m³ using 5- and 10-kJ ignition sources. In the 1-m³ chamber there was no change in the inerting level.

In the 20-L Siwek chamber there does appear to be a strong relationship between ignition energy and inerting level. Using a 1-kJ ignition source, the inerting level was determined to be 49% rock dust; this increased to 67% and 74% for 5-kJ and 10-kJ sources, respectively. These observations are similar to those made by Cashdollar and Chatrathi (1992) for the dependence of the minimum explosible concentration (MEC) on ignition energy. The strength of the ignition source had a greater influence on the MEC in the

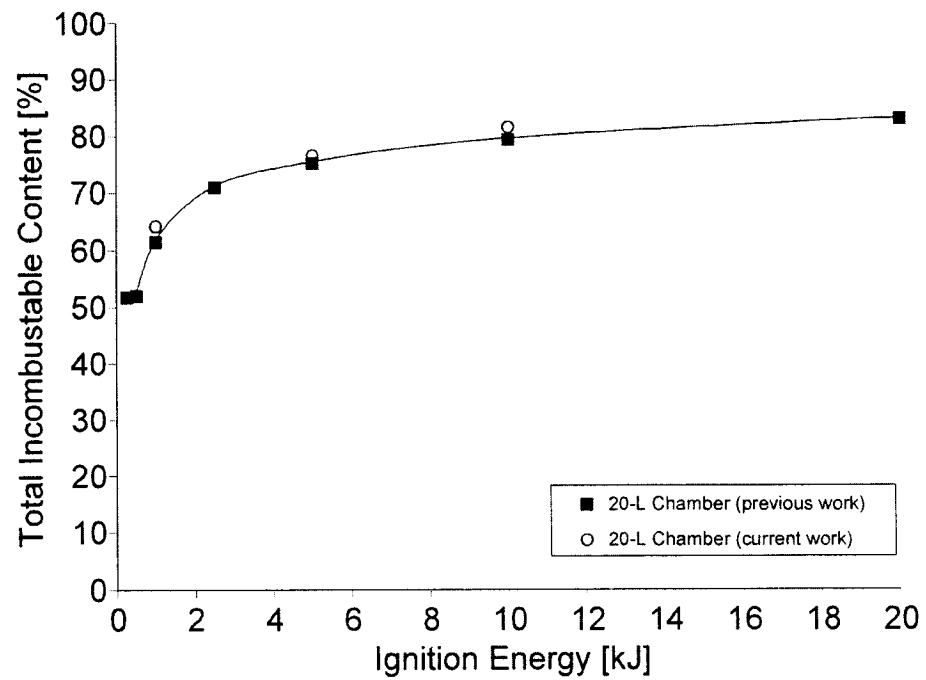


Figure 9.5: Percent total incombustible content required to inert as a function of ignition energy for mine-size coal dust.

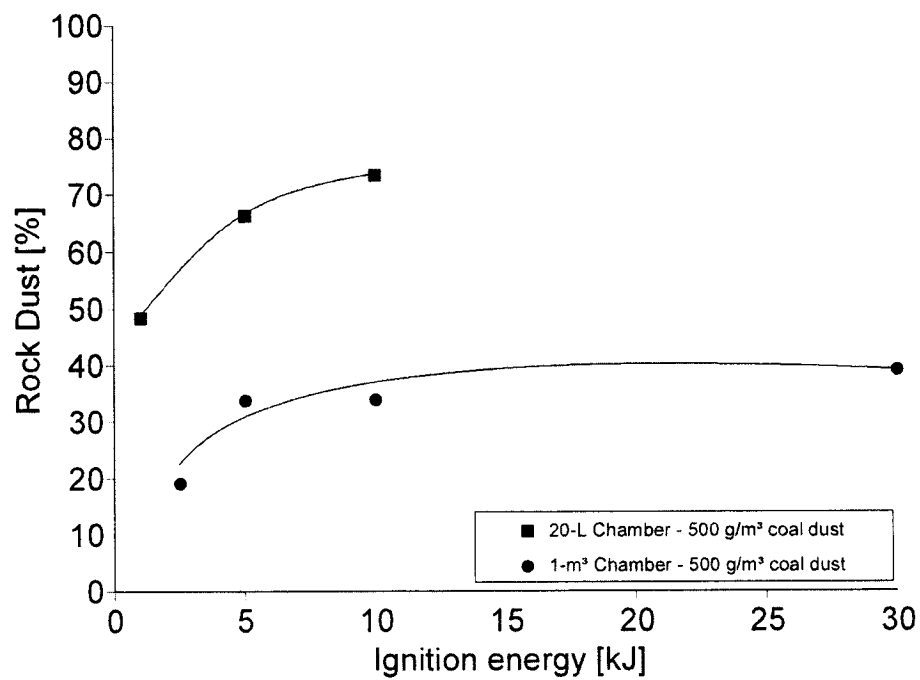


Figure 9.6: Percent rock dust required to inert as a function of ignition energy for mine-size coal dust in 1-m³ and 20-L chambers.

20-L chamber than in the 1-m³ chamber. The authors attributed the lower MEC's in the 20-L chamber to overdriving. These results also appear to support the comments made by Zhen and Leuckel (1997); the smaller 20-L chamber is affected by the ignition energy to a greater extent than the 1-m³ chamber.

These findings shed new light on previous results of inerting levels. The favorable comparison between USBM LLEM inerting levels and those determined in the 20-L Siwek chamber (which prompted the current study) may have been somewhat coincidental. The strong ignition energy used in the 20-L volume may have overdriven the chamber, resulting in a high inerting level. Inerting levels determined in the LLEM may be greatly affected by flame acceleration and pressure piling in the long mine gallery (leading to an increase in the amount of inertant required to prevent an explosion). Roughly, the small-chamber overdriving may equate to increased burning due to flame acceleration in the mine. Regardless, though, the mine-scale experiments replicate a specific industrial scenario; the inerting levels determined in the LLEM are representative of those required in that scenario. Attempts to match those inerting levels through manipulation of test variables (e.g. ignition energy) in 20-L testing, are attempts to replicate the full-scale mine scenario.

Ignition energy does not influence the determination of the peak overpressure as greatly where there is a significant level of combustion. The energy released from the burning dust cloud is significantly greater than that of the ignition source. This can be seen by the similarity in overpressure measurements determined in the different chambers. However, in limit conditions such as the MEC and inerting level determination, the energy-to-volume ratio of the ignition source could play an important role. This may imply that test conditions in the 20-L chamber should be varied according to the type of process hazard being examined: stronger ignition sources being used when results are to be extrapolated to mine galleries or silos (geometries with high L/D ratios), and weaker ignition sources when comparing the smaller vessel results to those from intermediate-scale vessels (or geometries with low L/D ratios).

9.5.2 Minimum Inerting Concentration Results From the 1-m³ Chamber

This work has been previously presented by Dastidar *et al.* (1998). Figures 9.7 and 9.8 show results of aluminum dust explosion overpressure measurements. Both figures show the overpressure as a function of concentration of pure aluminum, the optimum being between 750 - 1000 g/m³.

From Figures 9.7 and 9.8 it is apparent that as fuel concentration increases, the percent inertant required to prevent an explosion decreases. In the case of sodium bicarbonate as the inertant, the explosion was prevented with an inertant concentration between 55 and 60 % for fuel concentrations below 750 g/m³, and between 50 and 55 % for higher fuel concentrations. With monoammonium phosphate, 60 to 65 % inertant is required to prevent an explosion at concentrations below 1000 g/m³, and 55 to 60% is required for higher concentrations; for the highest concentration tested (2500 g/m³), 50 to 55 % inertant was required. Sodium bicarbonate required slightly less material to inert an explosion than monoammonium phosphate.

It is important to note that while the percent inertant in the mixture required to prevent an explosion decreased, the absolute mass of inertant required to prevent an explosion continued to increase. As a result no true MIC was observed for the inerting of aluminum with sodium bicarbonate or monoammonium phosphate at the concentrations tested. This can be seen in Figure 9.9 where the mass of fuel is plotted against the estimated mass of inertant required to prevent an explosion. The estimated mass was determined by calculating the median concentration between the lowest amount of inertant that did not produce an explosion and the greatest amount of inertant that did produce an explosion for a given fuel concentration. However, the observation that there is a decrease in the relative inertant concentration may mean that the inerting envelope is very broad and the MIC exists at a concentration that has not been tested.

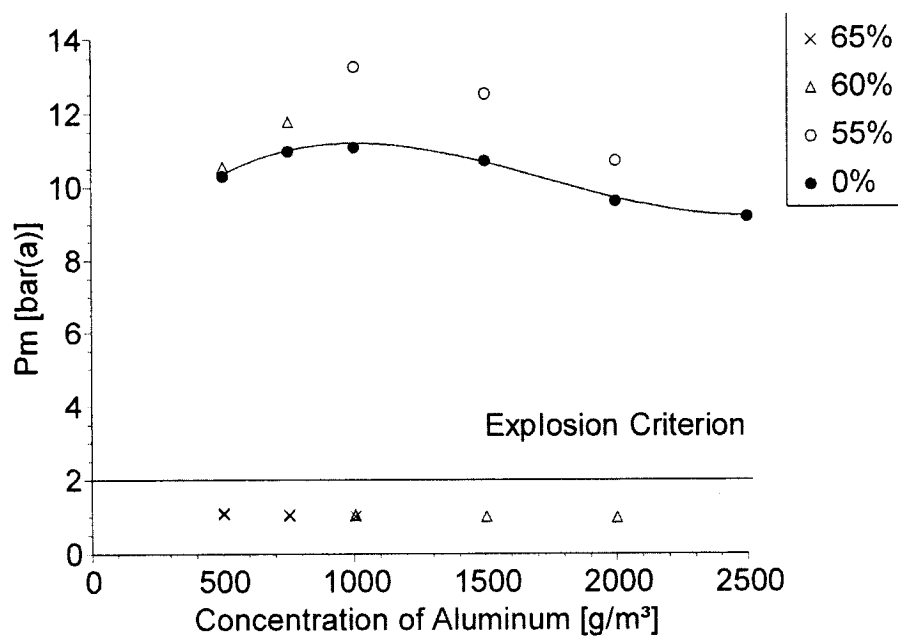


Figure 9.7: Explosion overpressure plotted against aluminum concentration for different amounts of monoammonium phosphate in mixture. Experiments conducted in a spherical 1-m³ chamber using two 5-kJ ignitors as an ignition source.

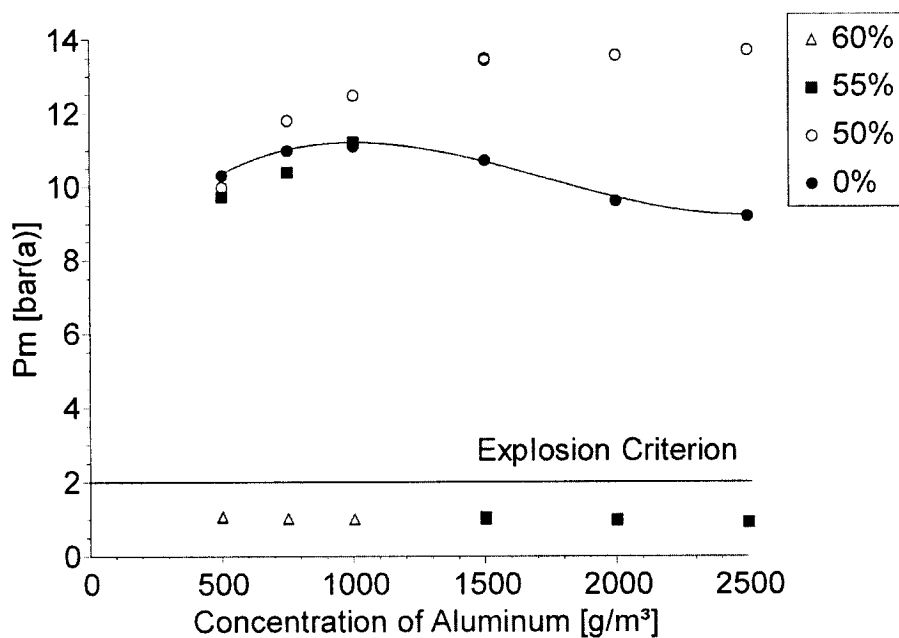


Figure 9.8: Explosion overpressure plotted against aluminum concentration for different amounts of sodium bicarbonate in mixture. Experiments conducted in a spherical 1- m^3 chamber using two 5-kJ ignitors as an ignition source.

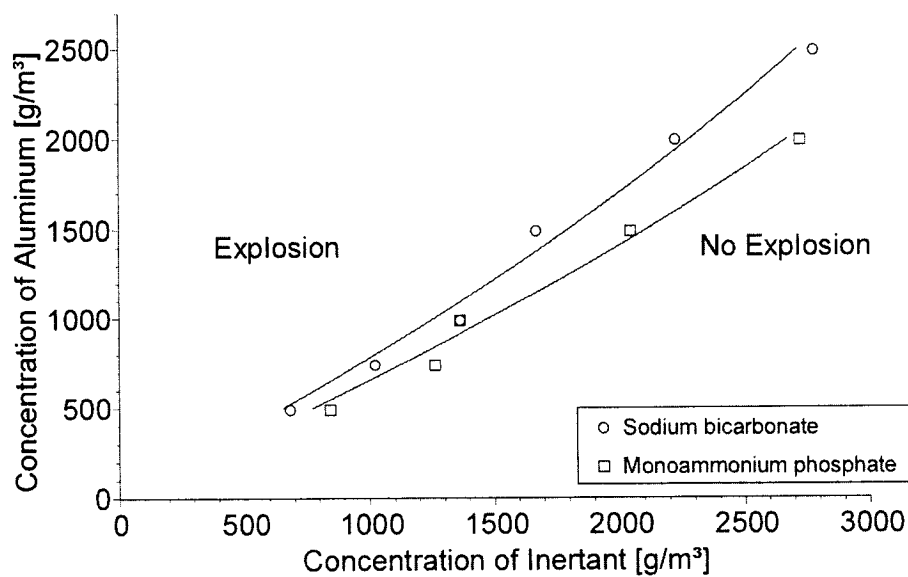


Figure 9.9: Comparison of monoammonium phosphate and sodium bicarbonate inerting curves for aluminum dust. Experiments conducted in a spherical 1-m³ chamber using two 5-kJ ignitors as an ignition source.

A phenomenon observed in the inerting of aluminum was that if insufficient inertant is used in the fuel/inertant mixture, the explosion overpressure is enhanced to levels greater than that for the pure dust. This phenomenon has been termed SEEP (Suppressant Enhanced Explosion Parameter). It can be attributed to decomposition of the inertant by heat from the combustion of the aluminum. In the case of sodium bicarbonate, carbon dioxide is produced and for monoammonium phosphate, ammonia and hydrogen, both flammable gases, are produced. This raises a concern for the inerting of hot burning metal dusts. If insufficient suppressant is present, this could lead to greater dangers than if no suppressant were used.

Figures 9.10 and 9.11 show results of anthraquinone dust explosion overpressure measurements. Both figures show the overpressure as a function of concentration of pure anthraquinone, the optimum being at 500 g/m³.

Both Figures 9.10 and 9.11 show a trend similar to that seen in the experiments for aluminum: as fuel concentration increases, the percent inertant required to prevent an explosion decreases. For monoammonium phosphate, 55 to 60 % inertant is required to prevent an explosion at concentrations below 750 g/m³, and 50 to 55% inertant is required for higher concentrations. This trend seems to remain constant for the fuel concentration range tested. The percent inertant may decrease if fuel concentration is increased further. With sodium bicarbonate as the inertant, the explosion was prevented with an inertant concentration between 75 and 80 % for low fuel concentrations. This suppression level steadily drops to between 60 and 65% at 1000 g/m³, showing a significant dependence of the inerting level on fuel concentration.

Figure 9.12 is obtained if the inerting results are plotted in a similar manner as the aluminum results. Here, the concentration of fuel is plotted against the concentration of inertant. It is apparent that inerting anthraquinone with monoammonium phosphate does not result in an MIC within the range of fuel concentrations tested. However, the inerting results with sodium bicarbonate clearly show an MIC occurring at about 1700 g/m³ of inertant. It should also be noted

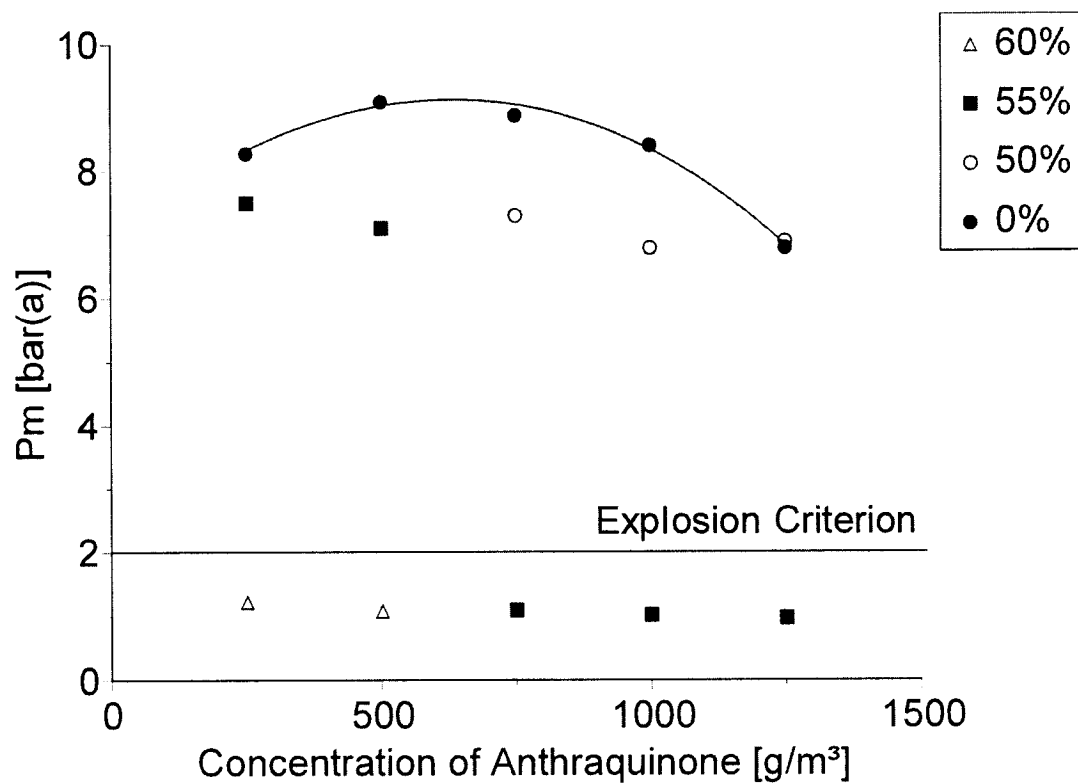


Figure 9.10: Explosion overpressure plotted against anthraquinone concentration for different amounts of monoammonium phosphate in mixture. Experiments conducted in a spherical 1- m^3 chamber using two 5-kJ ignitors as an ignition source.

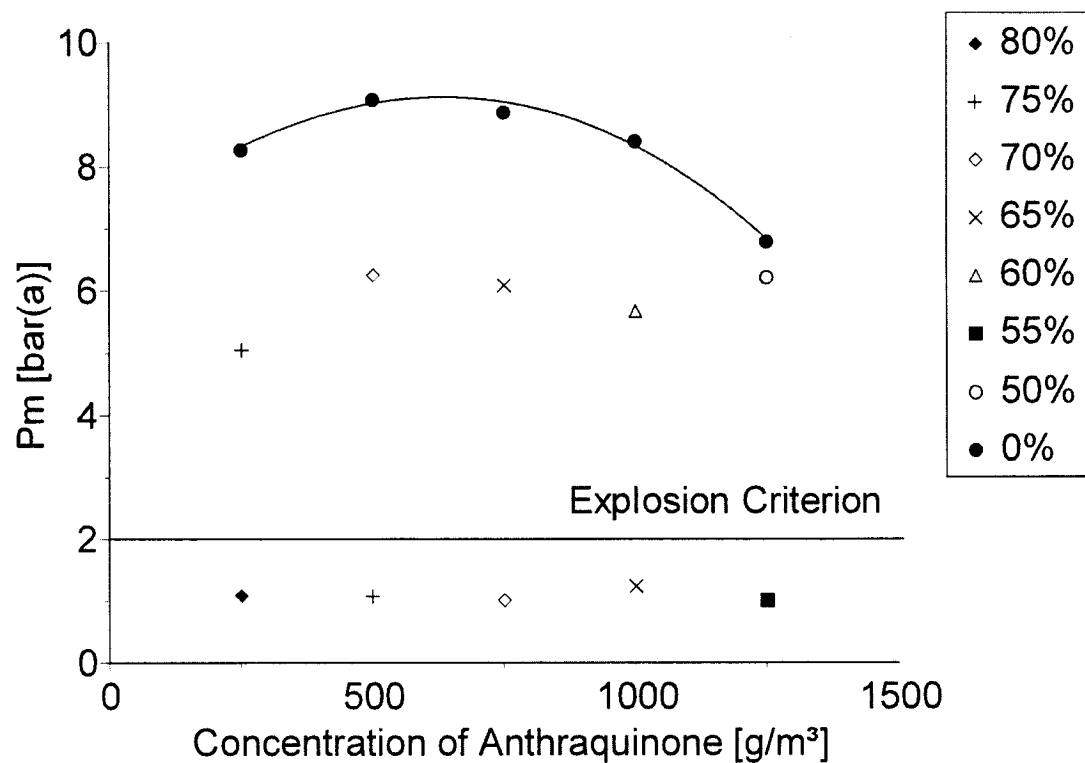


Figure 9.11: Explosion overpressure plotted against anthraquinone concentration for different amounts of sodium bicarbonate in mixture. Experiments conducted in a spherical 1- m^3 chamber using two 5-kJ ignitors as an ignition source.

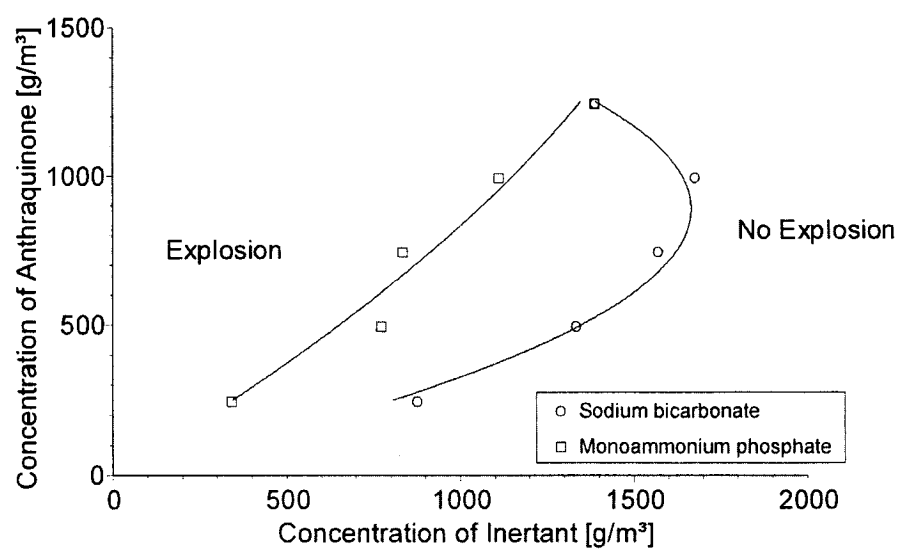


Figure 9.12: Comparison of monoammonium phosphate and sodium bicarbonate inerting curves for anthraquinone dust. Experiments conducted in a spherical 1-m³ chamber using two 5-kJ ignitors as an ignition source.

that monoammonium phosphate required less material to inert an explosion than sodium bicarbonate.

Figures 9.13 and 9.14 show results of polyethylene dust explosion overpressure measurements. As in the previous figures, the overpressure of the pure dust as a function of concentration is shown, the optimum being at 250 g/m³.

In Figures 9.13 and 9.14, the trend observed previously, is repeated. For monoammonium phosphate, 60 to 65 % inertant is required to prevent an explosion at 250 g/m³; this relative amount decreases to between 35 and 40% at 1500 g/m³. The percent inertant may decrease if fuel concentration is increased further. With sodium bicarbonate as the inertant, the explosion was prevented with an inertant concentration between 70 and 75 % for low fuel concentrations. This suppression level steadily drops to between 35 and 40% at 1500 g/m³, showing a significant dependence of the inerting level on fuel concentration.

The figures also demonstrate the SEEP phenomenon. The behavior is similar to that observed for aluminum inerting. When insufficient inertant to prevent an explosion is used, the resulting overpressure is greater than that observed for the pure fuel dust. For polyethylene, this occurred at all concentrations tested when using monoammonium phosphate as an inertant. However, when sodium bicarbonate was used as a suppressant, the SEEP phenomenon was only observed at the higher concentrations (> 1000 g/m³). The high rate of combustion of polyethylene may lead to the decomposition of the inertant.

In Figure 9.15, the concentration of fuel is plotted against the concentration of inertant in a similar manner as the aluminum results. It can be seen that inerting polyethylene with either monoammonium phosphate or sodium bicarbonate does not result in an MIC within the range of fuel concentrations tested. Inerting results with sodium bicarbonate show a slight curvature, thus hinting at the possibility of an MIC forming. The data show that monoammonium phosphate required less material to inert an explosion than sodium bicarbonate at low fuel concentrations, but at higher concentrations the inerting levels became similar.

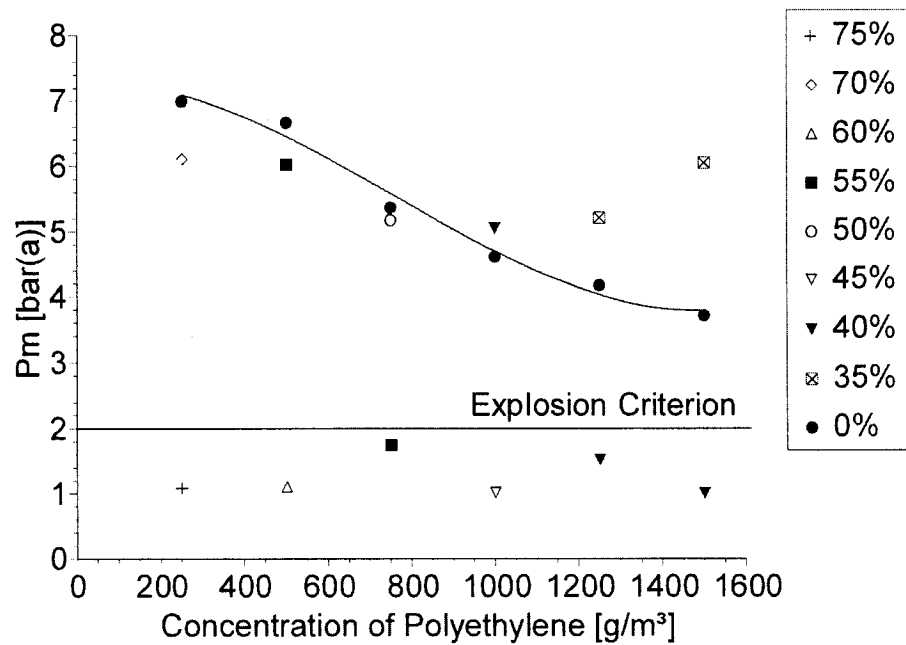


Figure 9.13: Explosion overpressure plotted against polyethylene concentration for different amounts of monoammonium phosphate in mixture. Experiments conducted in a spherical 1-m³ chamber using two 5-kJ ignitors as an ignition source.

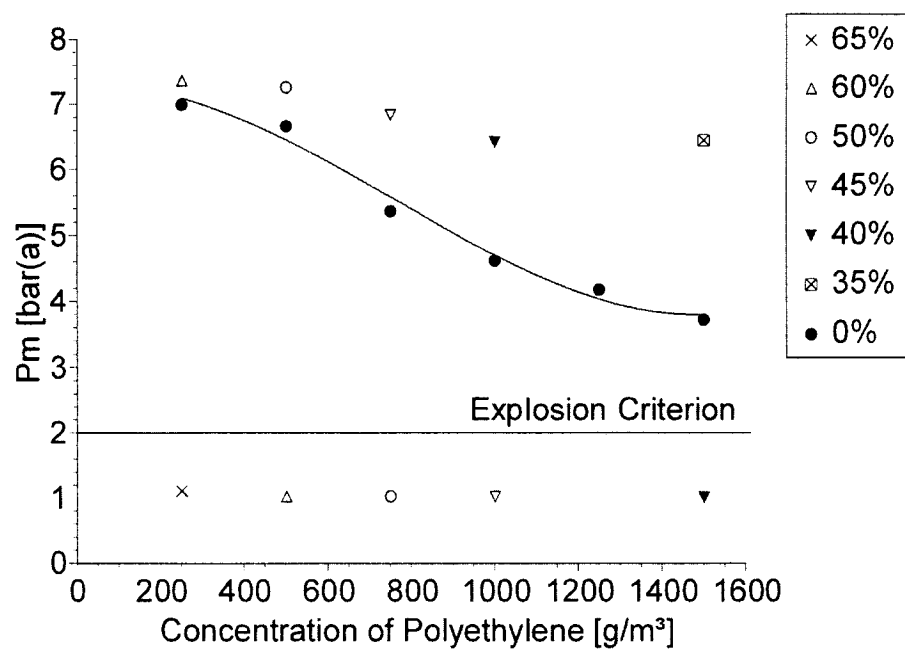


Figure 9.14: Explosion overpressure plotted against polyethylene concentration for different amounts of sodium bicarbonate in mixture. Experiments conducted in a spherical 1- m^3 chamber using two 5-kJ ignitors as an ignition source.

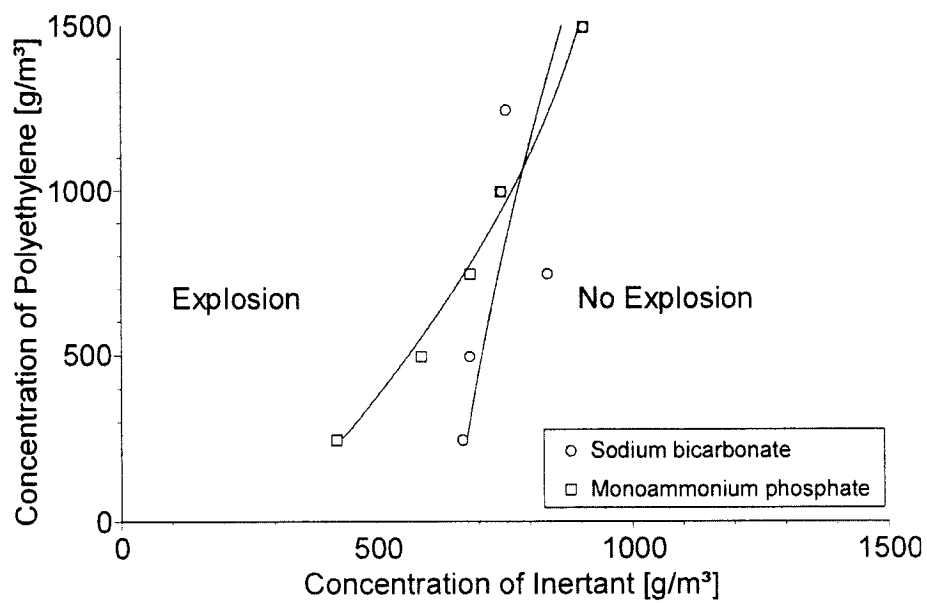


Figure 9.15: Comparison of monoammonium phosphate and sodium bicarbonate inerting curves for polyethylene dust. Experiments conducted in a spherical 1-m³ chamber using two 5-kJ ignitors as an ignition source.

All the results from the inerting experiments show a similar relationship. There is a definite relationship between the relative amount of inertant required to prevent an explosion and the fuel concentration. In all cases the relative amount of inertant decreased as fuel concentration increased. However, when the quantity of inertant is expressed in absolute terms in an inerting envelope, this trend becomes harder to see. In the case of inerting anthraquinone with sodium bicarbonate, there does appear to be a definite MIC at around 1700 g/m³ of inertant. In all the other cases there is no clear MIC in the concentration ranges tested. The other inerting envelopes may sweep out and form an MIC outside the range tested.

It could be argued that even though an MIC was not detected, the data do show the amount of inertant required to prevent an explosion for a broad fuel concentration range. This in itself is useful because it provides an indication of the amount of inertant that would be required to prevent an explosion if a reasonable quantity of dust were suspended. For example, if in a particular process situation it has been determined that a process upset would not produce an aluminum dust concentration greater than 2500 g/m³, then a suppression scheme can be devised so that the appropriate amount of inert matter will be used as a suppressant. The results from the current work show that an inertant concentration greater than 3000 g/m³ of monoammonium phosphate or sodium bicarbonate will prevent an explosion. This large amount of inertant will also prevent explosions at lower concentrations of aluminum. This information can then be used to design an explosion suppression scheme for any aluminum processing equipment so that the concentration of inertant (monoammonium phosphate or sodium bicarbonate) is greater than 3000 g/m³.

For safety reasons, it may be prudent not to use monoammonium phosphate to inert aluminum dust explosions. If insufficient quantities of this inertant are used, not only will it allow the explosion to proceed, but the heat from combustion will decompose the monoammonium phosphate producing combustible ammonia and hydrogen gas. It should be noted that several aluminum experiments that were insufficiently inerted in the current work produced large jet flames from the exhaust of the test vessel.

Another interesting result was the varying effectiveness of the two suppressants. Previous work at Fike has shown that monoammonium phosphate is a “better” inertant than sodium bicarbonate because less monoammonium phosphate is required to inert than sodium bicarbonate (for Pittsburgh pulverized coal and cornstarch, as shown in Figures 9.1 and 9.2). This agrees with results from Hertzberg *et al.* (1984) and Amrogowicz and Kordylewski (1991), both of whom have shown that for premixed inerting experiments in small chambers (~20 L), monoammonium phosphate is more effective than sodium bicarbonate. However, Amrogowicz and Kordylewski (1991) argued that in suppression testing, sodium bicarbonate performed better than ammonium phosphate. The authors argued that the discrepancy was the result of the different abilities of monoammonium phosphate and sodium bicarbonate to devolatilize, as well as the different chemical kinetics of ignition and flame propagation. It is possible that monoammonium phosphate is better at preventing an ignition kernel from forming and starting a combustion wave propagating through the unburned dust. Sodium bicarbonate’s effectiveness may be due to its ability to form chain terminating radicals in the combustion zone.

The experimental results from this work show that the organic fuels are inerted more effectively with monoammonium phosphate than sodium bicarbonate at low fuel concentrations. At higher fuel concentrations, sodium bicarbonate becomes more effective than monoammonium phosphate for simple organic compounds such as polyethylene and anthraquinone. Aluminum, the only metal tested, showed results where sodium bicarbonate performed marginally better as a inertant. This may be due to the nature of combustion. Aluminum dust combustion produces a very violent explosion. It has a much higher maximum overpressure and rate of pressure rise than all of the other dusts tested. In the case of coal, cornstarch, polyethylene and anthraquinone, the explosions were not as violent, with lower overpressures and rates of pressure rise observed. This in turn means that these organic dusts have relatively colder flames and slower rates of combustion. The ability of monoammonium phosphate to absorb and dissipate heat may favor these lower rates of combustion. The violence of the aluminum dust explosion may overwhelm monoammonium phosphate’s ability to absorb heat quickly enough to be as effective.

It should be noted that the sodium bicarbonate used here has a smaller mean particle size diameter than the monoammonium phosphate. It would be necessary to conduct experiments using inerting agents of similar particle size distributions to make a more conclusive statement as to which inertant is more effective for a given fuel type. However, comparing their inerting effectiveness across the fuel types tested is possible.

Higher rates of combustion of the fuel dust may lead to the decomposition of the inertant. This can be seen in the aluminum and polyethylene explosions. These were so violent that they lead to the decomposition of a significant quantity of inertant (in explosible mixtures of fuel and inertant). This created overpressures that were greater than the overpressures observed for the fuel dust alone.

It is also apparent from the experimental data presented here and previous work done at Fike that simple organic molecules such as cornstarch, polyethylene and anthraquinone do not generally form distinct inerting envelopes in the fuel concentration range tested. As a result they do not show a distinct MIC (except for cornstarch and anthraquinone inerting with sodium bicarbonate), while a complex organic fuel, such as coal dust does form a distinct inerting envelope. The “nose” indicating the MIC is easily seen. Sodium bicarbonate may be more effective than monoammonium phosphate at absorbing heat from the explosion quickly enough to prevent propagation, resulting in an MIC for anthraquinone and cornstarch.

The energy delivery rate from the combustion of simple organic compounds may be too fast for the inertant to absorb sufficient energy quickly enough to prevent combustion. This, in conjunction with the fact that these simple organic molecules have lower energy requirements to start combustion (low minimum ignition energy levels), may lead to a broad sweeping inerting envelope from which the MIC cannot easily be detected. Experiments at higher concentrations are hindered by physical limitations of the test vessel.

9.5.3 Minimum Inerting Concentration Results from the 20-L Siwek Chamber

Figure 9.16 graphs the results from the inerting envelope tests performed in the 20-L Siwek chamber using anthraquinone as a fuel and sodium bicarbonate and monoammonium phosphate as an inertant. These results are then compared to those from the previously described 1-m³ experiments. As can be seen, there is a similar trend to that observed for inerting level determination of CBDC mine-size coal dust. The inerting levels in the 20-L chamber are considerably higher for both inertants than in the 1-m³ chamber (i.e. more inertant is required to prevent an explosion in a 20-L volume using a 5-kJ ignition source than in a 1-m³ volume using a 10-kJ ignition source). It is also apparent that there are no “noses” in the inerting “envelopes” for the 20-L data. Both these observations may be attributed to a strong ignition source overdriving the test chamber. Because the inerting level is strongly dependent on the ignition energy (as shown by Dastidar *et al.* (1997) and in the work presented here), lower ignition energies may be required to produce an inerting envelope similar to that found in the 1-m³ chamber.

Both the inerting level determination experiments with coal dust, and the MIC experiments with anthraquinone presented here, show that more inertant is required in the 20-L chamber to prevent an explosion than in the 1-m³ chamber. Thus, the relative importance of wall quenching may be questionable due to the specific nature of the test method. By experimenting on premixed fuel and inertant dusts, the ignition limit is being tested. Because ignition occurs in the centre of the chamber, the inertant quenches the flame before it can reach the vessel wall. It is therefore possible that the inerting level is mostly dependent on the ignition energy (relative to volume size) used for testing.

Additional tests on other fuel types are necessary to characterize this apparent relationship between inerting level and ignition energy. It is important to determine if the inerting levels of different types of fuels are influenced to the same extent by the strength of the ignition source.

This work is currently underway in our laboratory. Further inerting tests are being performed in the 20-L Siwek chamber using aluminum, anthraquinone, polyethylene,

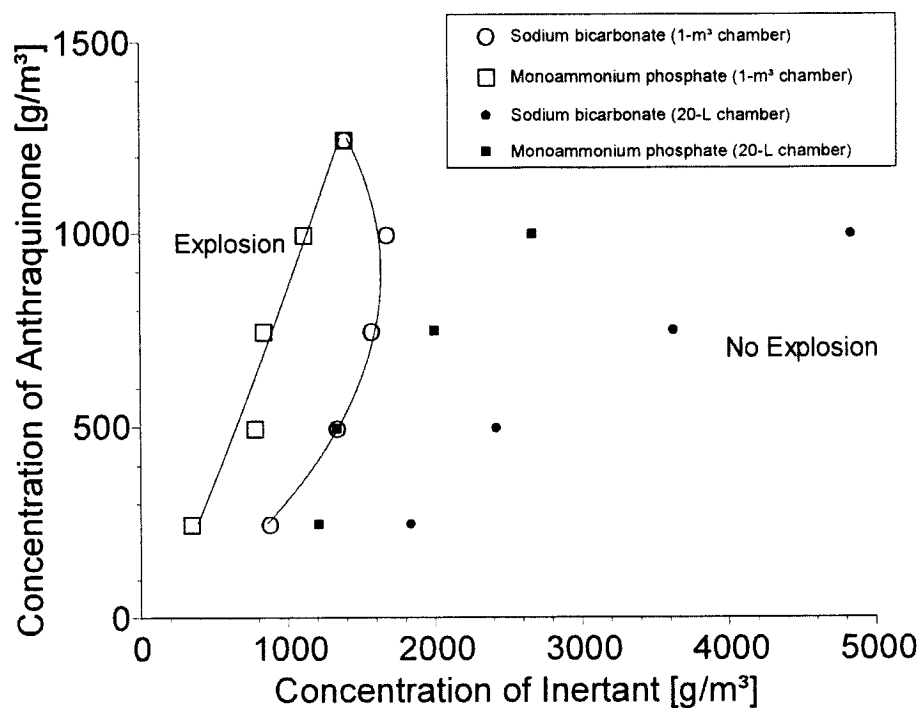


Figure 9.16: Comparison of monoammonium phosphate and sodium bicarbonate inerting curves for anthraquinone dust in 1-m³ and 20-L chambers. Experiments were conducted in the 1-m³ chamber using two 5-kJ ignitors as an ignition source. Experiments were conducted in the 20-L chamber using one 5-kJ ignitor as an ignition source.

Pittsburgh pulverized coal and cornstarch as fuels, and monoammonium phosphate and sodium bicarbonate as inertants. These tests are being conducted at different ignition energies to determine the most appropriate energy for best comparison to 1-m³ results.

9.6 CONCLUSIONS

The inerting level for mine-size CBDC coal dust using rock dust has been determined in the 1-m³ chamber and compared to inerting levels determined in the 20-L Siwek chamber. The 1-m³ inerting levels were lower than those found in the 20-L chamber. This may be caused by too strong an ignition energy overdriving the smaller chamber. Agreement between the 20-L chamber (using a 5-kJ ignition source) and mine-scale inerting levels may be due to overdriving of the smaller chamber reproducing the effects of flame acceleration on mine-scale results. It is possible that test conditions for inerting level determination have to be modified depending on the scale to which the results will be extrapolated. This may imply the use of relatively weak ignition sources for geometries with low L/D ratios and high ignition energies for geometries with high L/D ratios.

Inerting envelopes were produced in the 1-m³ chamber for aluminum, anthraquinone and polyethylene using monoammonium phosphate and sodium bicarbonate as inertants.

The relationship between the relative amount of inertant required to prevent an explosion and the fuel concentration has been shown. In all cases the relative amount of inertant decreased as fuel concentration increased. However, when the quantity of inertant is expressed in absolute terms in an inerting envelope, this trend becomes harder to see. For some of the fuel and inertant mixtures tested, there were no definitive MIC's.

Preliminary tests done to compare inerting levels determined in an intermediate-scale vessel (1-m³) with a laboratory-scale vessel (20-L) show evidence of overdriving in the smaller vessel (for both coal dust explosion inerting and MIC determination testing). Inerting levels were significantly higher in the 20-L chamber (using one 5-kJ ignitor as an ignition source) than in the 1-m³ chamber (using two 5-kJ ignitors as an ignition source).

Use of less energetic ignition sources in laboratory-scale vessels may be required to give inerting level results similar to those determined in intermediate-scale vessels.

Previous work at Fike (1998), and work by Hertzberg *et al.* (1984) and Amrogowicz and Kordylewski (1991), have shown that for premixed inerting experiments monoammonium phosphate is a more effective suppressant than sodium bicarbonate. The experimental results from this work in a 1-m³ vessel agree with their findings that the organic fuels require less monoammonium phosphate to inert an explosion than sodium bicarbonate at low fuel concentrations. At higher fuel concentrations, sodium bicarbonate became more effective than monoammonium phosphate for simple organic compounds such as polyethylene and anthraquinone. This is similar to the inerting envelope of cornstarch in Figure 9.2. It appears that for coal, a more complex organic fuel, monoammonium phosphate remains a more effective suppressant at high fuel concentrations. Aluminum was inerted marginally better by sodium bicarbonate. This may be due to the nature of combustion. Monoammonium phosphate may be a more effective suppressant suited to inert slower, low-temperature burning of organic fuels, while sodium bicarbonate may be better suited for faster, hotter metal combustion.

The combustion of aluminum, as well as polyethylene, was violent enough to lead to the decomposition of a significant quantity of inertant, leading to explosion parameters that were higher than those observed for the pure dust. This phenomenon has been termed Suppressant Enhanced Explosion Parameter by Fike and given the acronym SEEP. This may pose a challenge when designing an explosion suppression scheme since the use of insufficient quantities of suppressant may increase the hazard from the explosion.

Simple organic molecules such as polyethylene and anthraquinone do not form distinct inerting envelopes in the fuel concentration range tested. As a result, they do not form an MIC (except for anthraquinone inerting with sodium bicarbonate). The inerting envelope may only exist for complex organic compounds. The energy delivery rate from the combustion of simple organic compounds may be too fast for the inertant to absorb sufficient energy quickly enough to prevent combustion. This, in conjunction with low minimum ignition energy levels, may lead to a broad sweeping inerting envelope from

which the MIC cannot be detected in the concentration ranges tested. The alternative is to use a worst case scenario approach and use the highest absolute concentration of inertant required to prevent an explosion for the highest fuel range tested. This could lead to an effective MIC.

The new flammability limit parameter MIC described here has the potential of being an important tool in the design of explosion suppression systems. However, some fuel and inertant mixtures did not show an MIC in the concentration ranges tested. In these cases an effective MIC can be used. The effective MIC can be estimated by determining the maximum amount of fuel that can be suspended in air due to a process upset and finding the amount of inertant required to prevent an explosion for this concentration. Fuel concentrations below this maximum amount will also be inerted. The effective MIC can then be used as an estimate of the quantity of suppressant required to prevent an explosion.

9.7 ACKNOWLEDGEMENTS

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**10 APPENDIX B - DATA TABLES FOR INERTING EXPERIMENTS
IN THE FIKE 1-M³ SPHERICAL COMBUSTION CHAMBER**

Table 10.1: Inerting results for Aluminum powder with Sodium Bicarbonate in the 1-m³ chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [psi(a)]	Pm [bar(a)]	dP/dt [(psi/s)]	dP/dt [(bar/s)]	Vessel Pressure at Time of Ignition [psi(a)]
500	2,000	80	2×5	15.3	1.1	19	1	14.9
500	1,167	70	2×5	15.6	1.1	24	2	15.0
500	500	50	2×5	145.5	10.0	1719	119	15.3
500	750	60	2×5	16.4	1.1	34	2	15.2
500	611	55	2×5	141.7	9.8	1709	118	15.3
500	750	60	2×5	15.9	1.1	31	2	15.1
750	1,750	70	2×5	15.3	1.1	18	1	14.9
750	1,125	60	2×5	15.8	1.1	27	2	15.0
750	917	55	2×5	151.4	10.4	1465	101	15.4
750	1,125	60	2×5	15.4	1.1	19	1	14.9
1,000	1,222	55	2×5	163.1	11.2	1528	105	15.1
1,000	1,500	60	2×5	15.2	1.0	26	2	14.5
1,000	1,500	60	2×5	15.5	1.1	25	2	14.8
1,500	1,833	55	2×5	15.4	1.1	26	2	14.4
1,500	1,500	50	2×5	196.2	13.5	3364	232	14.8
1,500	1,833	55	2×5	15.9	1.1	64	4	14.4
1,500	1,500	50	2×5	195.4	13.5	3029	209	14.6
2,000	2,000	50	2×5	197.4	13.6	3517	243	14.2
2,000	2,444	55	2×5	14.9	1.0	31	2	14.1
2,000	2,444	55	2×5	15.0	1.0	31	2	14.2
750	750	50	2×5	171.7	11.8	3024	209	15.2
1,000	1,000	50	2×5	181.5	12.5	2905	200	14.9
1,000	429	30	2×5	177.0	12.2	3106	214	15.0
2,500	3,055	55	2×5	14.2	1.0	25	2	13.7
2,500	2,500	50	2×5	199.6	13.8	3048	210	13.9

Table 10.2: Inerting results for Aluminum powder with Monoammonium Phosphate in the 1-m³ chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [psi(a)]	Pm [bar(a)]	dP/dt [psi/s]	dP/dt [bar/s]	Vessel Pressure at Time of Ignition [psi(a)]
500	500	50	2×5	155.4	10.7	2871	198	NA*
500	750	60	2×5	153.8	10.6	1379	95	NA(18.4)*
500	1,167	70	2×5	16.0	1.1	33	2	15.2
500	929	65	2×5	16.8	1.2	31	2	15.2
500	929	65	2×5	16.2	1.1	35	2	15.1
500	500	50	2×5	156.1	10.8	2609	180	NA(148.3)*
500	500	50	0	0.0	0.0	0	0	NA*
500	500	50	2×5	0.0	0.0	0	0	NA*
500	500	50	2×5	169.0	11.7	2448	169	15.6
750	1,393	65	2×5	15.6	1.1	48	3	14.8
750	1,125	60	2×5	171.4	11.8	2313	159	15
750	1,393	65	2×5	16.0	1.1	56	4	14.9
1,000	1,857	65	2×5	15.6	1.1	46	3	14.6
1,000	1,500	60	2×5	15.8	1.1	43	3	14.9
1,000	1,222	55	2×5	193.1	13.3	2809	194	14.7
1,000	1,500	60	2×5	16.0	1.1	43	3	14.9
1,500	1,833	55	2×5	182.3	12.6	1938	134	14.6
1,500	2,250	60	2×5	15.2	1.0	48	3	14.2
2,000	2,444	55	2×5	156.0	10.8	428	29	14.2
2,000	3,000	60	2×5	14.7	1.0	32	2	14
2,500	3,056	55	2×5	14.2	1.0	25	2	13.7
2,500	2,500	50	2×5	199.6	13.8	3048	210	13.9

* Questionable initial pressure or ignition

Table 10.3: Inerting results for Anthraquinone powder with Sodium Bicarbonate in the 1-m³ chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [psi(a)]	Pm [bar(a)]	dP/dt [psi/s]	dP/dt [bar/s]	Vessel Pressure at Time of Ignition [psi(a)]
250	-	0	2×5	120.4	8.3	1063	73	15.7
500	-	0	2×5	132.3	9.1	1772	122	15.5
750	-	0	2×5	129.3	8.9	1897	131	15.5
1,000	-	0	2×5	122.5	8.5	2377	164	15.4
250	250	50	2×5	100.5	6.9	516	36	15.7
250	306	55	2×5	98.8	6.8	574	40	15.5
250	375	60	2×5	99.7	6.9	568	39	15.5
250	583	70	2×5	92.5	6.4	455	31	15.5
250	750	75	2×5	73.8	5.1	204	14	15.2
250	1,000	80	2×5	16.3	1.1	35	2	15.2
500	1,500	75	2×5	16.0	1.1	33	2	14.8
500	1,167	70	2×5	91.3	6.3	239	16	14.9
1,000	2,333	70	2×5	14.9	1.0	33	2	14.4
1,000	1,500	60	2×5	82.9	5.7	128	9	14.7
1,000	1,857	65	2×5	18.5	1.3	26	2	14.5
750	1,393	65	2×5	88.9	6.1	302	21	14.6
750	1,750	70	2×5	15.3	1.1	32	2	14.6
1,250	1,875	60	2×5	15.1	1.0	21	1	14.3
1,250	1,528	55	2×5	15.1	1.0	68	5	14.2
1,250	1,250	50	2×5	90.7	6.3	242	17	14.3

Table 10.4: Inerting results for Anthraquinone powder with Monoammonium Phosphate in the 1-m³ chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [psi(a)]	Pm [bar(a)]	dP/dt [psi/s]	dP/dt [bar/s]	Vessel Pressure at Time of Ignition [psi(a)]
250	583	70	2×5	16.5	1.1	37	3	15.4
250	375	60	2×5	18.1	1.2	47	3	15.6
250	306	55	2×5	27.0	1.9	41	3	15.5
250	250	50	2×5	120.7	8.3	1059	73	15.6
250	306	55	2×5	109.2	7.5	560	39	15.4
500	611	55	2×5	99.0	6.8	325	22	15.2
500	611	55	2×5	108.0	7.5	442	31	15.1
500	750	60	2×5	16.0	1.1	28	2	15.2
750	917	55	2×5	16.3	1.1	32	2	15.0
750	750	50	2×5	106.4	7.3	801	55	15.0
1,000	1,000	50	2×5	99.1	6.8	572	39	14.8
1,000	1,222	55	2×5	15.3	1.1	33	2	14.6
1,250	1,250	50	2×5	100.5	6.9	240	17	14.5
1,250	1,528	55	2×5	14.5	1.0	25	2	14.1

Table 10.5: Inerting results for Polyethylene powder with Sodium Bicarbonate in the 1-m³ chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	P _m [psi(a)]	P _m [bar(a)]	dP/dt [psi/s]	dP/dt [bar/s]	Vessel Pressure at Time of Ignition psi(a)
250	750	75	2×5	16.2	1.1	22	2	15.4
250	464	65	2×5	85	5.9	266	18	15.4
250	583	70	2×5	74.6	5.1	194	13	15.3
250	750	75	2×5	15.9	1.1	25	2	15.1
500	1,167	70	2×5	15.6	1.1	20	1	15.0
500	929	65	2×5	36.6	2.5	40	3	15.1
500	929	65	2×5	15.8	1.1	24	2	15.0
500	750	60	2×5	16.4	1.1	23	2	15.1
500	500	50	2×5	89.7	6.2	311	21	15.4
500	611	55	2×5	87.7	6.0	209	14	15.2
750	750	50	2×5	75.4	5.2	147	10	15.2
750	917	55	2×5	37.5	2.6	58	4	14.9
750	1,125	60	2×5	16.2	1.1	28	2	14.9
750	917	55	2×5	25.7	1.8	29	2	15.1
1,000	1,222	55	2×5	15.7	1.1	21	1	14.8
1,000	1,000	50	2×5	15.4	1.1	22	2	14.9
1,000	818	45	2×5	15.7	1.1	28	2	15.0
1,000	667	40	2×5	73.7	5.1	98	7	15.1
1,500	643	30	2×5	93.5	6.4	304	21	14.8
1,500	808	35	2×5	87.8	6.1	239	16	14.6
1,500	1,000	40	2×5	61.3	4.2	67	5	14.4

Table 10.6: Inerting results for Polyethylene powder with Monoammonium Phosphate in the 1-m³ chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [psi(a)]	Pm [bar(a)]	dP/dt [psi/s]	dP/dt [bar/s]	Vessel Pressure at Time of Ignition [psi(a)]
250	464	65	2×5	16.4	1.13	43	3	15.0
250	375	60	2×5	107.2	7.39	464	32	15.1
500	825	62	2×5	15.1	1.04	29	2	15.3
500	672	57	2×5	15.4	1.06	43	3	15.1
500	500	50	2×5	105.6	7.28	479	33	15.0
750	750	50	2×5	15.2	1.05	29	2	14.9
750	613	45	2×5	99.5	6.86	305	21	14.9
1,000	818	45	2×5	15.1	1.04	43	3	15.0
1,000	666	40	2×5	93.5	6.45	406	28	15.0
1,500	807	35	2×5	94.0	6.48	218	15	14.9
1,500	1,000	40	2×5	14.9	1.03	29	2	14.8

Table 10.7: Inerting CBDC Mine-size Coal Dust with regular rock dust in the 1-m³ chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [psi(a)]	Pm [bar(a)]	dP/dt [psi/s]	dP/dt [bar/s]	Vessel Pressure at Time of Ignition [psi(a)]
500	929	65	5	15.0	1.0	21	1	14.8
500	500	50	5	16.0	1.1	19	1	15.3
500	333	40	5	16.0	1.1	15	1	15.3
500	214	30	5	94.0	6.5	294	20	15.5
500	269	35	5	16.0	1.1	17	1	15.5
500	269	35	5	16.0	1.1	21	1	15.4
500	333	40	2×5	17.0	1.2	36	2	15.5
500	269	35	2×5	17.0	1.2	36	2	15.4
500	214	30	2×5	92.0	6.3	250	17	15.1
500	269	35	2×5	19.0	1.3	37	3	15.1
500	333	40	6×5	18.0	1.2	33	2	15.6
500	269	35	6×5	106.0	7.3	412	28	15.5
500	333	40	6×5	19.0	1.3	65	4	15.4
500	214	30	2.5	16.1	1.1	22	1	15.6
500	167	25	2.5	16.5	1.1	19	1	15.7
500	0	0	2.5	123.7	8.5	800	55	15.7
500	125	20	2.5	16.0	1.1	17	1	15.5
500	56	10	2.5	121.6	8.4	834	58	15.5
500	88	15	2.5	118.1	8.1	846	58	15.1
500	125	20	2.5	16.3	1.1	18	1	15.5
1,000	429	30	2×5	113.3	7.8	575	40	15.2
1,000	538	35	2×5	18.7	1.3	48	3	15.2
1,000	429	30	5	82.4	5.7	140	10	15.2
1,000	538	35	5	15.9	1.1	29	2	15.1

Table 10.8: Inerting CBDC Mine-size Coal Dust with AIM Baghouse rock dust in the 1-m³ chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [psi(a)]	Pm [bar(a)]	dP/dt [psi/s]	dP/dt [bar/s]	Vessel Pressure at Time of Ignition [psi(a)]
500	214	30	2×5	16.8	1.2	30	2	15.5
500	167	25	2×5	16.8	1.2	36	2	15.5
500	125	20	2×5	54.1	3.7	75	5	15.3
500	167	25	2×5	18.3	1.3	32	2	15.5

**11 APPENDIX C - DATA TABLES FOR INERTING EXPERIMENTS
IN THE SIWEK 20-L SPHERICAL COMBUSTION CHAMBER**

Table 11.1: Inerting results for Aluminum powder with Sodium Bicarbonate in the 20-L chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	0	0	5	3.3	42
500	0	0	5	6.9	233
500	0	0	2×5	7.3	170
500	0	0	5	7.3	275
750	0	0	5	7.8	215
1,000	0	0	5	7	254
1,250	0	0	5	7.6	264
250	83	25	5	3.7	39
250	107	30	5	2.2	7
250	135	35	5	3.1	21
250	167	40	5	0	0
250	167	40	5	2.6	11
250	205	45	5	0.6	2
250	250	50	5	0.2	2
250	250	50	5	0	0
250	583	70	5	0	0
250	1,000	80	5	0	0
500	500	50	5	7.3	106
500	611	55	5	0	0
500	611	55	5	3.2	179
500	750	60	5	0	0
500	750	60	5	0	0
500	1,167	70	5	0	0
750	750	50	5	8.3	100
750	917	55	5	2.8	9
750	1,125	60	5	0	0
750	1,125	60	5	0	0
1,000	1,000	50	5	9.9	212
1,000	1,222	55	5	7.9	75
1,000	1,500	60	5	0	0
1,000	1,500	60	5	0	0
1,250	1,528	55	5	8.3	76
1,250	1,875	60	5	0	0
1,250	1,875	60	5	0	0

Table 11.2: Inerting results for Aluminum powder with Monoammonium Phosphate in the 20-L chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	107	30	5	5	64
250	135	35	5	2.9	32
250	167	40	5	0.1	0
250	167	40	5	3	38
250	205	45	5	0.4	0
250	205	45	5	3.5	51
250	250	50	5	0.2	2
250	250	50	5	0.1	0
500	500	50	5	7.4	123
500	611	55	5	5.2	66
500	750	60	5	0	0
500	750	60	5	0	0
750	1,125	60	5	4.8	24
750	1,393	65	5	0	0
750	1,393	65	5	0	0
1,000	1,000	50	5	8.2	76
1,000	1,222	55	5	7	52
1,000	1,500	60	5	0	0
1,000	1,500	60	5	2.6	21
1,000	1,857	65	5	0	0
1,250	1,875	60	5	1.4	7
1,250	2,321	65	5	0	0
1,250	2,321	65	5	0	0

Table 11.3: Inerting results for Anthraquinone powder with Sodium Bicarbonate in the 20-L chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	0	0	5	8.6	1,085
500	0	0	5	9	1,251
750	0	0	5	8.1	1,040
1,000	0	0	5	7.5	849
250	1,000	80	5	4.9	38
250	1,417	85	5	0.8	8
250	1,417	85	5	1.6	8
250	2,250	90	5	0	0
500	2,833	85	5	0	0
500	2,000	80	5	5	34
500	2,833	85	5	0.6	6
750	3,000	80	5	4.9	24
750	4,250	85	5	0	0
750	4,250	85	5	0	0
1,000	2,333	70	5	5.1	68
1,000	3,000	75	5	4.8	31
1,000	4,000	80	5	4.3	20
1,000	5,667	85	5	0	0
500	1,500	75	1	0	0
500	1,167	70	1	4.6	50
500	1,500	75	1	4.8	52
500	2,000	80	1	0.1	22
750	1,750	70	1	4.3	18
750	2,250	75	1	0	0
750	2,250	75	1	0	0
1,000	2,333	70	1	3.6	18
1,000	3,000	75	1	0	0
1,000	3,000	75	1	0	0

Table 11.4: Inerting results for Anthraquinone powder with Monoammonium Phosphate in the 20-L chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	750	75	5	5.2	60
250	1,000	80	5	4.3	11
250	1,417	85	5	0	0
250	1,417	85	5	0	0
500	2,000	80	5	0	0
500	1,167	70	5	5.5	78
500	1,500	75	5	No Ignition	
500	1,500	75	5	0	0
500	1,500	75	5	0	0
750	1,750	70	5	4.9	40
750	2,250	75	5	0.8	0
750	2,250	75	5	0	0
1,000	2,333	70	5	No Ignition	
1,000	1,857	65	5	5.2	126
1,000	2,333	70	5	3.8	19
1,000	2,333	70	5	4.1	21
1,000	3,000	75	5	0	0

Table 11.5: Inerting results for Cornstarch powder with Sodium Bicarbonate in the 20-L chamber using a 5-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	0	0	5	4.1	43
500	0	0	5	7.8	464
750	0	0	5	9	632
1,000	0	0	5	8.9	468
1,250	0	0	5	8.7	509
250	167	40	5	1	14
250	205	45	5	3.8	28
250	250	50	5	0.8	5
250	250	50	5	6.4	30
250	306	55	5	4	24
250	375	60	5	0	0
250	375	60	5	3.8	16
250	464	65	5	0.1	2
250	464	65	5	0.4	11
500	929	65	5	5.6	29
500	1,167	70	5	4.8	10
500	1,500	75	5	0.3	3
500	1,500	75	5	0	0
750	1,125	60	5	5.7	35
750	1,393	65	5	0	0
750	1,393	65	5	5.4	11
750	1,750	70	5	0	0
750	1,750	70	5	0	0
750	2,250	75	5	0	0
1,000	818	45	5	6.6	34
1,000	1,000	50	5	0	0
1,000	1,000	50	5	0	0
1,000	1,222	55	5	0	0
1,000	1,857	65	5	0	0
1,250	673	35	5	6.3	37
1,250	833	40	5	0	0
1,250	833	40	5	6	22
1,250	1,023	45	5	0	0
1,250	1,023	45	5	5.6	26

Table 11.6: Inerting results for Cornstarch powder with Sodium Bicarbonate in the 20-L chamber using a 1-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
500	500	50	1	0.2	10
500	409	45	1	0.5	5
500	333	40	1	1	32
500	269	35	1	6.1	64
500	333	40	1	3.5	12
750	500	40	1	0	0
750	404	35	1	0	0
750	321	30	1	1.3	8
750	404	35	1	6.3	44
750	500	40	1	0	0
1,000	429	30	1	0	0
1,000	333	25	1	0	0
1,000	250	20	1	0	0
1,000	176	15	1	0	0
1,000	111	10	1	8.2	160
1,000	176	15	1	0	0

Table 11.7: Inerting results for Cornstarch powder with Monoammonium Phosphate in the 20-L chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	375	60	5	1.2	12
250	464	65	5	0.5	0
250	464	65	5	0.7	11
500	929	65	5	0	0
500	750	60	5	4.6	14
500	929	65	5	0	0
750	1,393	65	5	0	0
750	1,125	60	5	0	0
750	917	55	5	4.1	8
750	1,125	60	5	0	0
1,000	1,222	55	5	0.6	30
1,000	1,000	50	5	0.1	32
1,000	818	45	5	0	0
1,000	667	40	5	6.9	100
1,000	818	45	5	0	0
1,250	833	40	5	6.8	58
1,250	833	40	5	Ignitor no go	
1,250	1,023	45	5	5.6	24
1,250	1,250	50	5	0	0

Table 11.8: Inerting results for Cornstarch powder with Limestone in the 20-L chamber.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	P _m [bar(g)]	dP/dt [bar/s]
250	1,000	80	5	0	0
250	583	70	5	4.2	31
250	750	75	5	3	20
250	1,000	80	5	0.2	5
250	1,000	80	5	1.2	12
250	1,417	85	5	0	0
500	1,500	75	5	4.9	62
500	2,000	80	5	3.3	19
500	2,833	85	5	0	0
500	2,833	85	5	0	0
750	3,000	80	5	2	6
750	4,250	85	5	0	0

Table 11.9: Inerting results for Pittsburgh Pulverized Coal Dust with Sodium Bicarbonate in the 20-L chamber using a 5-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	P _m [bar(g)]	dP/dt [bar/s]
250	0	0	5	6.1	101
500	0	0	5	7.8	343
750	0	0	5	7.3	420
1,000	0	0	5	7.1	384
1,250	0	0	5	6.2	373
1,500	0	0	5	6	352
250	583	70	5	3.8	24
250	1,000	80	5	0	0
250	750	75	5	0	0
250	750	75	5	0.9	9
500	1,500	75	5	0	0
500	1,167	70	5	4.6	12
500	1,500	75	5	0	0
750	1,750	70	5	0	0
750	1,393	65	5	0.1	0
750	1,125	60	5	4.3	24
750	1,393	65	5	4	14
750	1,750	70	5	0	0
1,000	2,333	70	5	0	0
1,000	1,500	60	5	3.8	6
1,000	1,857	65	5	0	0
1,000	1,857	65	5	3.6	37

Table 11.10: Inerting results for Pittsburg Pulverized Coal Dust with Sodium Bicarbonate in the 20-L chamber using a 1-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	375	60	1	0.2	18
250	306	55	1	0.3	15
250	205	45	1	4.9	58
250	250	50	1	4.6	54
250	306	55	1	0.2	20
500	500	50	1	5.7	64
500	611	55	1	5.4	64
500	750	60	1	4.9	12
500	929	65	1	0.1	0
500	929	65	1	0.4	10
750	1,125	60	1	0.1	11
750	750	50	1	5.5	66
750	917	55	1	0	0
750	917	55	1	0.1	0
1,000	1,000	50	1	0	0
1,000	667	40	1	0.1	3
1,000	429	30	1	5.7	58
1,000	538	35	1	5	91
1,000	667	40	1	4.8	43
1,000	818	45	1	0	0
1,250	536	30	1	5.1	110
1,250	833	40	1	4.9	39
1,250	1,023	45	1	4.7	16
1,250	1,250	50	1	0	0
3,000	0	0	1	4.1	22

Table 11.11: Inerting results for Pittsburg Pulverized Coal Dust with Monoammonium Phosphate in the 20-L chamber using a 5-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	P _m [bar(g)]	dP/dt [bar/s]
250	250	50	5	2.3	18
250	375	60	5	0.7	19
250	375	60	5	0.8	10
250	306	55	5	1.6	19
500	611	55	5	0.9	22
500	611	55	5	0.2	27
500	500	50	5	4.5	17
750	750	50	5	0.5	14
750	614	45	5	1.7	14
750	750	50	5	0.3	19
1,000	667	40	5	0.1	0
1,000	538	35	5	5	39
1,000	667	40	5	0	0
1,000	667	40	5	0	0
1,250	1,023	45	5	0	0
1,250	833	40	5	0.5	17
1,250	673	35	5	4.8	40
1,250	833	40	5	3.9	5
1,250	833	40	5	0.3	35
1,500	808	35	5	0.2	42
1,500	643	30	5	0	0
1,500	500	25	5	0	0
1,500	265	15	5	4.6	58
1,500	375	20	5	5	29
1,500	500	25	5	0.7	6

Table 11.12: Inerting results for Pittsburgh Pulverized Coal Dust with Monoammonium Phosphate in the 20-L chamber using a 2.5-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	250	50	2.5	0.3	0
250	167	40	2.5	0.7	21?
250	0	0	2.5	3.7	16
250	107	30	2.5	0.5	6
250	63	20	2.5	1.2	8
250	83	25	2.5	1.6	11
250	107	30	2.5	0.3	4
500	214	30	2.5	4.4	10
500	333	40	2.5	0.3	8
500	269	35	2.5	0.5	4
500	269	35	2.5	0.9	8
750	321	30	2.5	0.5	8
750	250	25	2.5	5.2	35
750	321	30	2.5	0.3	4
1,000	333	25	2.5	0.3	4
1,000	250	20	2.5	0	0
1,000	176	15	2.5	6.2	113
1,000	250	20	2.5	0	0
1,250	221	15	2.5	5.5	75
1,250	313	20	2.5	0.3	2
1,250	313	20	2.5	0.2	1
1,500	265	15	2.5	5	26
1,500	375	20	2.5	0	0
2,000	353	15	2.5	0.1	0
2,000	105	5	2.5	4.1	26
2,000	222	10	2.5	0.2	4
2,000	222	10	2.5	0	0

Table 11.13: Inerting results for Pittsburgh Pulverized Coal Dust with Monoammonium Phosphate in the 20-L chamber using a 1-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	28	10	1	0.6	16
250	13	5	1	6.3	140
250	28	10	1	1	18
500	56	10	1	6.9	178
500	88	15	1	6.6	132
500	125	20	1	5.4	28
500	167	25	1	0.3	22
500	167	25	1	0.2	14
750	188	20	1	0.5	12
750	132	15	1	0.1	0
750	83	10	1	6.5	201
750	132	15	1	0.2	12
1000	111	10	1	6.2	139
1000	176	15	1	5.8	59
1000	250	20	1	0.1	0
1000	250	20	1	0.3	17
1250	221	15	1	0.1	0
1250	139	10	1	0	0
1250	66	5	1	6	76
1250	139	10	1	0.4	5
1500	79	5	1	5.2	68
1500	167	10	1	0.2	14?
1500	167	10	1	0.1	0

Table 11.14: Inerting results for Pittsburgh Pulverized Coal Dust with Monoammonium Phosphate in the 20-L chamber using a 0.5-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	0	0	0.5	0.2	13
250	205	45	0.5	0.1	0
250	250	50	0.5	0.1	0
500	0	0	0.5	7.2	234
500	56	10	0.5	4.3	20
500	88	15	0.5	0.5	15
500	88	15	0.5	1.7	16
500	125	20	0.5	0.4	12
500	125	20	0.5	0.5	13
750	39	5	0.5	6.6	230
750	83	10	0.5	0.2	13
750	83	10	0.5	5.8	102
750	132	15	0.5	0.2	18
750	132	15	0.5	0	0
1,000	0	0	0.5	6.6	212
1,000	53	5	0.5	0	0
1,000	53	5	0.5	5.9	169
1,000	111	10	0.5	0	0
1,000	111	10	0.5	0.2	8
1,250	66	5	0.5	6	113
1,250	139	10	0.5	0	0
1,250	139	10	0.5	0.1	0

Table 11.15: Inerting results for Pittsburgh Pulverized Coal Dust with Limestone in the 20-L chamber using a 5-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	1,000	80	5	0	0
250	750	75	5	0.1	0
250	583	70	5	2.3	15
250	750	75	5	0.2	0
500	1,167	70	5	4.5	11
500	1,500	75	5	0	0
500	1,500	75	5	0.2	0
750	1,750	70	5	0	0
750	1,125	60	5	4.9	46
750	1,393	65	5	4.7	17
750	1,750	70	5	4.1	10
750	1,750	70	5	0	0
1,000	1,857	65	5	4.8	27
1,000	2,333	70	5	0	0
1,000	2,333	70	5	0	0
1,000	2,333	70	5	0.5	0

Table 11.16: Inerting results for Polyethylene with Sodium Bicarbonate in the 20-L chamber using a 5-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	0	0	5	6.5	266
500	0	0	5	7.6	527
750	0	0	5	6.6	606
1,000	0	0	5	5.9	430
1,250	0	0	5	5.2	327
250	583	70	5	2.7	36
250	750	75	5	3.6	24
250	1,000	80	5	0	0
250	1,000	80	5	0	0
500	929	65	5	4.6	53
500	1,167	70	5	4.7	42
500	1,500	75	5	0	0
500	1,500	75	5	0	0
750	1,125	60	5	5.1	29
750	1,393	65	5	0	0
750	1,393	65	5	0	0
750	1,750	70	5	0	0
1,000	1,222	55	5	5.1	32
1,000	1,500	60	5	0	0
1,000	1,500	60	5	4.8	23
1,000	1,857	65	5	0	0
1,000	1,857	65	5	0	0
1,250	1,250	50	5	2.3	8
1,250	1,528	55	5	0.2	2
1,250	1,528	55	5	3.6	15
1,250	1,875	60	5	0	0
1,250	1,875	60	5	0	0

Table 11.17: Inerting results for Polyethylene with Monoammonium Phosphate in the 20-L chamber using a 5-kJ ignition source.

Fuel Concentration [g/m ³]	Inertant Concentration [g/m ³]	Percent Inertant [%]	Ignition Energy [kJ]	Pm [bar(g)]	dP/dt [bar/s]
250	583	70	5	5.3	82
250	750	75	5	3.9	28
250	1,000	80	5	0.1	2
250	1,000	80	5	0	0
500	929	65	5	5.6	59
500	1,167	70	5	0.4	2
500	1,167	70	5	0	0
500	1,500	75	5	0	0
750	1,393	65	5	4.3	47
750	1,750	70	5	0	0
750	1,750	70	5	0	0
1,000	1,222	55	5	5.3	29
1,000	1,500	60	5	0	0
1,000	1,500	60	5	4.6	21
1,000	1,857	65	5	0	0
1,000	1,857	65	5	0.3	2
1,250	1,875	60	5	4.1	12
1,250	2,321	65	5	0.2	25
1,250	2,321	65	5	0	0

**12 APPENDIX D - DATA TABLES FOR INERTING LEVEL
DEPENDENCE ON IGNITION SOURCE ENERGY**

Table 12.1: Inerting level of Aluminum in the 1-m³ and 20-L chambers using various ignition sources.

Aluminum [g/m ³]	Inertant Concentration Required to Mitigate an Explosion in a 1-m ³ chamber [g/m ³]		Inertant Concentration Required to Mitigate an Explosion in a 20-L chamber [g/m ³]	
	Sodium bicarbonate 10-kJ ignition source	Monoammonium phosphate 10-kJ ignition source	Sodium bicarbonate 5-kJ ignition source	Monoammonium phosphate 5-kJ ignition source
250			186	228
500	681	840	681	681
750	1021	1259	1021	1259
1000	1361	1361	1361	1679
1250			1702	2098
1500	1667	2042		
2000	2222	2722		
2500	2778			

Table 12.2: Inerting level of Anthraquinone in the 1-m³ and 20-L chambers using various ignition sources.

Anthraquinone [g/m ³]	Inertant Concentration Required to Mitigate an Explosion in a 1-m ³ chamber [g/m ³]		Inertant Concentration Required to Mitigate an Explosion in a 20-L chamber [g/m ³]		
	Sodium bicarbonate 10-kJ ignition source	Monoammonium phosphate 10-kJ ignition source	Sodium bicarbonate 5-kJ ignition source	Sodium bicarbonate 1-kJ ignition source	Monoammonium phosphate 5-kJ ignition source
250	875	340	1833		1208
500	1333	770	2416	1750	1333
750	1571	833	3625	2000	2000
1000	1679	1111	4833	2667	2667
1250	1390	1389			

Table 12.3: Inerting level of Cornstarch in the 1-m³ and 20-L chambers using various ignition sources.

Inertant Concentration Required to Mitigate an Explosion in a 1-m ³ chamber [g/m ³]			
Cornstarch [g/m ³]	Sodium bicarbonate 10-kJ ignition source	Monoammonium phosphate 10-kJ ignition source	Limestone 10-kJ ignition source
85			
125			
250	278	151	875
500	455	301	1333
750	286	362	2000
1000	213	602	2667
1250		604	
1500		571	
1750		667	

Inertant Concentration Required to Mitigate an Explosion in a 20-L chamber [g/m ³]				
Cornstarch [g/m ³]	Sodium bicarbonate 5-kJ ignition source	Sodium bicarbonate 1-kJ ignition source	Monoammonium phosphate 5-kJ ignition source	Limestone 5-kJ ignition source
85				
125				
250	420		420	1209
500	1334	371	840	2417
750	1572	452	1021	3625
1000	909	144	743	
1250	1137		1137	
1500				
1750				

Table 12.4: Inerting level of Pittsburgh Pulverized Coal Dust in the 1-m³ and 20-L chambers using various ignition sources.

Pittsburgh Pulverized Coal Dust [g/m ³]	Inertant Concentration Required to Mitigate an Explosion in a 1-m ³ -chamber [g/m ³]		
	Sodium bicarbonate 10-kJ ignition source	Limestone 10-kJ ignition source	Monoammonium phosphate 10-kJ ignition source
85	0	0	0
125	139		
250	341	278	21
500	455	681	72
750	557	834	108
1000	82	909	82
1250		1137	33
1500		1114	
1750		1055	
2000		762	

Pittsburgh Pulverized Coal Dust [g/m ³]	Inertant Concentration Required to Mitigate an Explosion in a 20-L-chamber [g/m ³]		
	Sodium bicarbonate 5-kJ ignition source	Sodium bicarbonate 1-kJ ignition source	Limestone 5-kJ ignition source
85			
125			
250	667	278	667
500	1334	840	1334
750	1572	834	1572
1000	2095	743	2095
1250		1137	
1500			

Pittsburgh Pulverized Coal Dust [g/m ³]	Inertant Concentration Required to Mitigate an Explosion in a 20-L-chamber [g/m ³]			
	Monoammonium phosphate 5-kJ ignition source	Monoammonium phosphate 2.5-kJ ignition source	Monoammonium phosphate 1-kJ ignition source	Monoammonium phosphate 0.5-kJ ignition source
85	0	0	0	0
125				
250	340	95	21	0
500	556	242	146	107
750	682	286	108	108
1000	602	213	213	82
1250	753	267	103	103
1500	438	320		

Table 12.5: Inerting level of Cornstarch in the 1-m³ and 20-L chambers.

Polyethylene [g/m ³]	Inertant Concentration Required to Mitigate an Explosion in a 1-m ³ chamber [g/m ³]		Inertant Concentration Required to Mitigate an Explosion in a 20-L chamber [g/m ³]	
	Sodium bicarbonate 10-kJ ignition source	Monoammonium phosphate 10-kJ ignition source	Sodium bicarbonate 5-kJ ignition source	Monoammonium phosphate 5-kJ ignition source
250	667	420	875	875
500	681	586	1334	1048
750	834	682	1259	1572
1000	743	742	1679	1679
1250	753		1702	2098
1500	904	904		

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Dear Catherine,

I am in the process on submitting my PhD thesis for my oral defense.

I am including the two articles I wrote for Process Safety and Environmental Protection:

"A. Dastidar and P. Amyotte, "Determination of minimum inerting concentrations for combustible dusts in a laboratory-scale chamber", Trans IChemE, Process Safety and Environmental Protection, vol. 80, Part B, pp. 287-297, 2002."

"A. Dastidar and P. Amyotte, "Using calculated adiabatic flame temperatures to determine dust explosion inerting requirements", Trans IChemE, Process Safety and Environmental Protection, Part B, March 2004 - in press."

as sections/chapters of my thesis. I am citing the original source of the publication, PSEP, in my thesis. However, I am wondering about copy write issues. I would like to use the whole articles as chapters for my thesis. The thesis will not be sold by me or the university.

Elsevier on

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My question is; does this allow me to use my articles published in PSEP in my thesis, whole, without violating your copy write? The article will have to be reformatted to meet university guidelines.

Regards,

Ashok

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