PROPAGATION AND SUPPRESSION OF GAS AND DUST EXPLOSIONS

P. E. Moore
Explosion suppression system design has relied historically on the validity of Hartmann apparatus explosibility test data, and on interpolation from available suppression system test data. This research has identified improved methods of explosion hazard assessment and suppression system efficacy assessment, from a study of explosion propagation, suppressant action, and discharge of suppressors.

The controversy over the validity of Hartmann dust explosibility data was resolved. It was found that the ignition methodology was responsible for the uncertainty of Hartmann data. A 43dm$^3$ spherical explosion test apparatus was developed which provided more useful explosibility data. The influence of turbulence on explosion hazards was recognised and an empirical measure of turbulence level was defined.

Systematic trials with suppressed and unsuppressed explosions were undertaken in a 1m$^3$ apparatus. The results of these trials provided the foundation for the development of a mathematical model of explosion suppression. A 6.2m$^3$ explosion test facility was set up in alignment with the requirements of a proposed International Standard. Explosion and explosion suppression trials in this apparatus substantiated the model. Certain artefacts were identified in 6.2m$^3$ quiescent gas explosions. An interactive computer program based on the model for explosion suppression was tested and proved.

The work has culminated in the establishment of a large-scale explosion test facility in the UK. The effectiveness of three suppressants, Halon 1011, water, and mono-ammonium phosphate powder, against both gas and dust explosions was established experimentally. The influence of
suppression system detection pressure and explosion suppressor discharge characteristics on the resultant suppression system effectiveness was determined experimentally. A computer model of explosion suppression has emerged which provides an improved level of confidence in adjudging the performance of explosion suppression measures.

Areas for further work include larger scale explosion and explosion suppression trials and a study of artefacts identified with large volume quiescent gas explosions.
This study would not have been possible without the support and commitment of my employer, Graviner Ltd., and I am indebted to Mr J.R. Stevens (Technical Director), and Dr R.L. Farquhar (Research Manager) for that support, and for permitting the work to be submitted for a collaborative degree.

I owe an enormous debt of gratitude to my supervisors, Dr B. Ray (Lanchester Polytechnic) and Prof. V. Griffiths (University of Surrey) for providing the necessary motivation, technical guidance and editorial advice. Their help proved invaluable at all stages of the work.

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In the course of this research I have had numerous helpful discussions with my colleagues and with fellow research workers in this field. In particular, I would like to thank those at:

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- Deugra Gmbh - Dusseldorf
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- Fire Research Station - Borehamwood
- Ciba Geigy Central Safety Division - Basle
- TNO Prins Maurits Laboratorium - Rijswijk
- CERCHAR - Verneuil-en-Halatte

Last, but not least, I thank my wife, Sharon, for her forebearance and support during the course of this study.

P.E. Moore

* Dr B. Ray was formerly Research Manager at Wilkinson Match Research
# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUMMARY</td>
<td>i</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>ii</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td>1.1. General Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2. Objectives</td>
<td>2</td>
</tr>
<tr>
<td>1.3. Status of Proposed International Standard</td>
<td>3</td>
</tr>
<tr>
<td>1.3.1. Collaborative Trials</td>
<td>4</td>
</tr>
<tr>
<td>1.4. Presentation of Material</td>
<td></td>
</tr>
<tr>
<td>1.4.1. Explosions</td>
<td>4</td>
</tr>
<tr>
<td>1.4.2. Suppressants</td>
<td>5</td>
</tr>
<tr>
<td>1.4.3. Suppressors</td>
<td>5</td>
</tr>
<tr>
<td>1.4.4. Suppression</td>
<td>5</td>
</tr>
<tr>
<td>2. LITERATURE REVIEW</td>
<td></td>
</tr>
<tr>
<td>2.1. Introduction to Explosion Theory</td>
<td>6</td>
</tr>
<tr>
<td>2.1.1. Thermal Explosions</td>
<td>6</td>
</tr>
<tr>
<td>2.1.2. Chain Reaction Explosions</td>
<td>7</td>
</tr>
<tr>
<td>2.1.3. Actual Explosions</td>
<td>9</td>
</tr>
<tr>
<td>2.2. Explosions</td>
<td></td>
</tr>
<tr>
<td>2.2.1. Theory of Explosion Pressure Development</td>
<td>10</td>
</tr>
<tr>
<td>2.2.2. Explosibility Scaling</td>
<td>12</td>
</tr>
<tr>
<td>2.2.3. Dust Explosion Propagation</td>
<td>12</td>
</tr>
<tr>
<td>2.2.4. Dust Explosibility Measurement</td>
<td>17</td>
</tr>
<tr>
<td>2.2.5. Explosion Test Results</td>
<td>19</td>
</tr>
<tr>
<td>2.2.5.1. Gas Explosibility Data</td>
<td>19</td>
</tr>
<tr>
<td>2.2.5.2. Dust Explosibility Data</td>
<td>20</td>
</tr>
<tr>
<td>2.3. Explosion Suppressants</td>
<td></td>
</tr>
<tr>
<td>2.3.1. Modes of Suppression</td>
<td>21</td>
</tr>
<tr>
<td>2.3.2. Halogenated Hydrocarbons (Halons)</td>
<td>22</td>
</tr>
<tr>
<td>2.3.2.1. Chemical Mechanisms</td>
<td>23</td>
</tr>
<tr>
<td>2.3.2.2. Physical Mechanisms</td>
<td>26</td>
</tr>
<tr>
<td>2.3.3. Powders</td>
<td></td>
</tr>
<tr>
<td>2.3.3.1. Homogeneous Suppression</td>
<td>27</td>
</tr>
<tr>
<td>2.3.3.2. Heterogeneous Suppression</td>
<td>30</td>
</tr>
<tr>
<td>2.3.4. Practical Applications</td>
<td>30</td>
</tr>
</tbody>
</table>
2.4. Explosion Suppressors
   2.4.1. Hemispherical Suppressor
   2.4.2. Cylindrical Suppressor
   2.4.3. High Rate Discharge (HRD) Suppressors
   2.4.4. Suppressor Manufacturers

2.5. Explosion Suppression
   2.5.1. Historical Development of Explosion Suppression Techniques
   2.5.2. Principles of Explosion Protection
   2.5.3. Explosion Suppression Systems
   2.5.4. Explosion Suppression Tests
      2.5.4.1. Coal Mine Tests
      2.5.4.2. Plant Simulation Tests
      2.5.4.3. Suppression System Efficacy Tests

3. THEORY

3.1. Explosions
   3.1.1. Explosion Development
   3.1.2. Turbulence
   3.1.3. Scaling and Interpretation of Explosion Data
   3.1.4. Ignition Criteria

3.2. Explosion Suppressants
   3.2.1. Halons
   3.2.2. Water
   3.2.3. Powders

3.3. Explosion Suppressors
   3.3.1. Hemispherical Suppressors
   3.3.2. High Rate Discharge (HRD) Suppressors
   3.3.3. Performance Analogues

3.4. Explosion Suppression
   3.4.1. A Thermal Model of Suppression Effectiveness
   3.4.2. Advanced Inerting
      3.4.2.1. Gaseous Phase Combustion
      3.4.2.2. Particulate Combustion
   3.4.3. Development of a Mathematical Model
   3.4.4. The Model
   3.4.5. The Computer Programme
4. EXPERIMENTAL METHOD

4.1. Explosions

4.1.1. Explosion Test Apparatus

4.1.1.1. 'Standard' Bartknecht Vessel

4.1.1.2. 'Standard' Hartmann Vertical Tube Apparatus

4.1.1.3. 'Experimental' 1:1 Aspect Ratio Vertical Tube Apparatus

4.1.1.4. 'Experimental' 43dm³ Spherical Test Apparatus

4.1.1.5. 'Experimental' 6.2m³ IEP Test Facility

4.1.2. Ignition Sources

4.1.2.1. Standard Ignition Procedures

4.1.2.2. Experimental Ignition Procedures

4.1.2.3. Development of a High Energy Capacitive Discharge Ignition Source

4.1.3. Control Unit

4.1.4. Mensuration

4.1.5. Test Procedures

4.1.5.1. Quiescent Gas Explosions

4.1.5.2. Turbulent Gas Explosions

4.1.5.3. Dust Explosions

4.1.6. Selection of Test Explosible Fuels

4.1.6.1. Gases

4.1.6.2. Dusts

4.2. Explosion Suppressants

4.2.1. Halons

4.2.2. Inert Gases

4.2.3. Powders

4.3. Explosion Suppressors

4.3.1. Experimental Arrangement

4.3.2. Preparation of HRD Suppressors

4.3.3. Mensuration

4.4. Explosion Suppression

4.4.1. Collaborative Trials using the Bartknecht 1m³ Vessel

4.4.2. Explosion Suppression Trials using the IEP Test Facility

4.5. The IEP Test Facility

4.5.1. The Chosen Strategy

4.5.2. Modifications to LPG Vaporiser

4.5.3. Site Preparations

4.5.4. The IEP Test Facility

4.5.5. Licensing, Insurance and Safety

4.5.6. Test Facility Instrumentation

4.5.7. Test Procedures

4.5.7.1. Unsuppressed Quiescent Gas Explosions

4.5.7.2. Unsuppressed Dust Explosions

4.5.7.3. Explosion Suppression Trials
5. RESULTS

5.1. Explosions

5.1.1. The Bartknecht 1m³ Vessel
5.1.1.1. Gas Explosion Tests
5.1.1.2. Dust Explosion Tests

5.1.2. The Hartmann Vertical Tube Apparatus
5.1.2.1. Gas Explosion Tests
5.1.2.2. Characterisation of Dust Dispersion
5.1.2.3. Dust Explosion Tests

5.1.3. The 1:1 Aspect Ratio Vertical Tube Apparatus
5.1.3.1. Gas Explosion Tests
5.1.3.2. Dust Explosion Tests

5.1.4. The 43dm³ Spherical Apparatus
5.1.4.1. Gas Explosions
5.1.4.2. Dust Explosions

5.1.5. The 6.2m³ IEP Test Vessel
5.1.5.1. Gas Explosion Tests
5.1.5.2. Dust Explosion Tests

5.2. Explosion Suppressants

5.3. Explosion Suppressors
5.3.1. Hemispherical Suppressors
5.3.2. High Rate Discharge (HRD) Suppressors
5.3.2.1. Standard Graviner HRD Suppressors
5.3.2.2. Influence of Fill Ratio
5.3.2.3. Influence of Propelling Agent Pressure
5.3.2.4. Influence of Outlet Orifice Area

5.4. Explosion Suppression
5.4.1. Suppressed Explosion Parameters
5.4.2. Collaborative Experiments in 1m³ Vessel
5.4.2.1. Datum Experiments
5.4.2.2. Gas Explosions
5.4.2.3. Dust Explosions

5.4.3. Suppression Trials in the 6.2m³ IEP Test Apparatus
5.4.3.1. Datum Experiments
5.4.3.2. Gas Explosions
5.4.3.3. Dust Explosions

6. DISCUSSION

6.1. Explosions
6.1.1. Quiescent Gas Explosions
6.1.2. Turbulent Gas Explosions
6.1.3. Dust Explosions
6.1.3.1. Hartmann Apparatus – An Appraisal
6.1.3.2. Development of the 43dm³ Apparatus
6.1.3.3. Comparison of Test Apparatus
<table>
<thead>
<tr>
<th>Plate</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Consequences of a secondary dust explosion</td>
<td>10</td>
</tr>
<tr>
<td>II</td>
<td>Explosion Suppressors</td>
<td>31</td>
</tr>
<tr>
<td>III</td>
<td>Bartknecht 1m³ Explosion Test Vessel</td>
<td>73</td>
</tr>
<tr>
<td>IV</td>
<td>Hartmann Vertical Tube Apparatus</td>
<td>74</td>
</tr>
<tr>
<td>V</td>
<td>1:1 Aspect Ratio Vertical Tube Apparatus</td>
<td>74</td>
</tr>
<tr>
<td>VI</td>
<td>43dm³ Spherical Explosion Test Apparatus</td>
<td>75</td>
</tr>
<tr>
<td>VII</td>
<td>100J Spark Ignition Apparatus</td>
<td>79</td>
</tr>
<tr>
<td>VIII</td>
<td>Control Unit</td>
<td>79</td>
</tr>
<tr>
<td>IX</td>
<td>Cellulose Dust Particle Size Analysis</td>
<td>92</td>
</tr>
<tr>
<td>X</td>
<td>Disused LPG Vaporiser</td>
<td>99</td>
</tr>
<tr>
<td>XI</td>
<td>6.2m³ IEP Test Facility</td>
<td>101</td>
</tr>
<tr>
<td>XII</td>
<td>Multiprobe Flame Proximity Detector</td>
<td>102</td>
</tr>
<tr>
<td>XIII</td>
<td>Dust Dispersion in the Hartmann Tube</td>
<td>113</td>
</tr>
<tr>
<td>XIV</td>
<td>Discharge Characteristic of 1dm³ Hemispherical Suppressor</td>
<td>138</td>
</tr>
<tr>
<td>XV</td>
<td>Discharge Characteristic of 3dm³ HRD Suppressor</td>
<td>139</td>
</tr>
<tr>
<td>XVI</td>
<td>Typical Explosion Suppression System Installation</td>
<td>154</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

1.1. General Background

This thesis is submitted for an industrial collaborative degree of PhD. The research was undertaken as part of a three year study programme at Graviner Ltd. in close liaison with the University of Surrey. The author was responsible for the whole study programme, which had both technical and commercial objectives. The author had limited access to the following scientists and technologists in the Graviner Company:

(i) research chemist;
(ii) computer programmer;
(iii) electrical engineer;
(iv) mechanical engineer.

These scientists provided valuable advice and project support as and when necessary. Research technician support was available to the author throughout the experimental programme.

Explosion protection by suppression has been established as a commercial alternative to other explosion protection procedures for some 25 years. The constraints placed upon the designers and suppliers of explosion suppression systems have increased as a consequence of recent safety legislation. The introduction shortly of a new International Standard (see section 1.3) will increase the requirement of a supplier to demonstrate that active explosion protection measures are designed with an assured operational effectiveness. The work described in this thesis arose out of the need to establish a more fundamental foundation for the design of explosion suppression systems on industrial plant, than that based on an unquestioned dependence on interpolation and interpretation of the collation of available test results.
1.2. Objectives

The research programme was started against a background of controversy and uncertainty regarding the validity of dust explosibility data obtained from UK and USA standard test procedures. In the United Kingdom, there was no large volume explosion test facility that would comply with the proposed International Standard requirements. The establishment and instrumentation of such an explosion test facility formed an important primary objective of the research programme. This objective had to be met within the limited financial resource available for the whole study.

An extensive review of all pertinent literature on gas and dust explosions, explosion suppressants, explosion suppressors, and explosion suppression was undertaken, both as a foundation for the research, and as a source of reference for other workers within this specific field of science and technology. The objectives of the study were:

1. to resolve the uncertainty/controversy regarding explosibility measurement of dust;

2. to establish a large volume explosion test facility in the United Kingdom in compliance with the proposals of ISO/TC21/SC5/WG3;

3. to establish a theoretical foundation for explosion hazard assessment;

4. to determine the performance characteristics of Graviner and Deugra industrial explosion suppressors;

5. to establish an understanding and foundation for the observed effectiveness and limitations of explosion suppressants;
6. to determine experimentally the performance characteristics of explosion suppression systems;

7. to establish sufficient understanding of explosion suppression to provide a basis for a mathematical model capable of experimental verification;

8. to set up, as appropriate, a computer-aided explosion suppression system design facility as a system design aid for a manufacturing company of explosion suppression systems.

1.3. Status of Proposed International Standard

The International Organisation for Standardisation (ISO) Technical Committee TC21 "Equipment for fire protection and fire fighting", Sub-Committee SC5 "Fixed fire extinguishing systems" established a Working Group WG3 "Explosion suppression systems" which first met in July 1975. The objectives of this working group were to appraise the status of explosion suppression technology and to establish a foundation for a draft International Standard on explosion suppression systems. The UK is represented by BSI and specific members of the appropriate BSI Committee (FSB/-/4/5) attend ISO/TC21/SC5/WG3 meetings. The author has represented Graviner Ltd. on FSB/-/4/5 since 1977 and has participated in the ISO/TC21/SC5/WG3 meetings. A small group of technologists was established within this ISO working group to collaborate on experimental trials of explosion suppression measures, and to appraise the technical problems associated with the preparation of such a standard. The author has participated in this group, and part of the research reported in this thesis reflects the activities and progress of this ISO Standard. Working drafts of the proposed standard are now available as discussion documents within WG3 (1-3).
1.3.1. Collaborative Trials

The series of explosion suppression trials undertaken by participant delegations of ISO/TC21/SC5/WG3 are listed below:

<table>
<thead>
<tr>
<th>ISO Delegation</th>
<th>Vessel Volume</th>
<th>Suppression System</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK/W Germany</td>
<td>1m$^3$</td>
<td>1 of 75mm diameter single outlet suppressor</td>
</tr>
<tr>
<td>USA</td>
<td>3.8m$^3$</td>
<td>2 of 75mm diameter single outlet suppressor</td>
</tr>
<tr>
<td>Switzerland</td>
<td>1m$^3$</td>
<td>1 of 19mm diameter double outlet suppressor</td>
</tr>
<tr>
<td>France</td>
<td>1m$^3$</td>
<td>1 of 19mm diameter double outlet suppressor</td>
</tr>
</tbody>
</table>

Explosion suppression experiments in the 1m$^3$ apparatus, described in section 5.4.2, were conducted by Dr E.W. Scholl at Bergbau Versuchsstrecke, Dortmund, in collaboration with the author, as part of UK/W Germany's contribution to ISO/TC21/SC5/WG3. The results of the other test programmes are summarised in Appendix 1.

1.4. Presentation of Material

It is implicit in such a research programme on explosion suppression that consideration must be given to explosions, suppressants, and suppressors to provide the necessary foundation for an understanding of explosion suppression. The material is presented in this thesis using the conventional structure, theory, methods, results, discussion and conclusions. However, it is subdivided into the four research areas of explosions, suppressants, suppressors and suppression, which permits the reader to follow one particular area of interest through the document without significant loss of continuity.
1.4.1. Explosions
Explosibility measurements using a defined experimental procedure are a prerequisite of industrial explosion hazard assessment. Quantification of the effectiveness of any proposed active explosion protection measure requires that the nature and severity of the explosion hazard is defined. The validity and limitations of established test procedures for gas and dust explosibility measurements are appraised as part of this study and a basis established to provide meaningful explosion hazard assessment.

1.4.2. Suppressants
The effectiveness of suppressants against the range of explosion hazards is quantified and a theoretical model evolved which establishes the criteria for effective suppression. The effectiveness of Halon, water, and ammonium phosphate powder suppressants are compared.

1.4.3. Suppressors
The influence of explosion suppressor parameters on their performance is evaluated, both theoretically and experimentally, and the discharge characteristics of explosion suppressors quantified to provide the necessary data to estimate the performance of explosion suppression systems.

1.4.4. Suppression
The work on explosion hazard assessment, suppressant effectiveness, and suppressor performance establishes a foundation for the development of a computer model of explosion suppression. The predictions of this model are compared with experimental data. The performance of different suppressants on both gas and dust explosions is determined experimentally in 1m$^3$ and 6.2m$^3$ test vessels.
The literature is extensive, and numerous conflicting reports exist in important areas. This review provides a general introduction into explosion theory with particular emphasis on suppression, followed by a comprehensive appraisal of the literature in the four areas of explosions, suppressants, suppressors and suppression.

2.1. Introduction to Explosion Theory

An exothermic chemical reaction liberates chemical energy as heat. If the rate of heat release in a reaction is greater than the rate of heat loss from the reaction zone then an explosion can result. In the context of this thesis, an explosion is defined specifically as a freely propagating combustion wave through a pre-mixed explosible fuel/air mixture. When contained, the consequence of such an explosion is a rapid increase in pressure caused by the expansion of the hot combustion products. Explosions involving combustion (4,5) can be broadly classified into two categories: thermal explosions and chain reaction explosions.

2.1.1. Thermal Explosions

In these, reaction acceleration occurs only as a result of heat liberated from reactions. Auto-acceleration occurs because the rate of reaction of the fuel with the oxidant varies exponentially with temperature, whereas heat transfer by conduction from the combustion zone depends linearly on temperature. This behaviour is shown diagramatically below.

![Diagram showing reaction rate and heat release vs temperature](image-url)
At a wall temperature $T_1$ and heat release $\leq H_3$, a stable combustion results at A. At a wall temperature $T_2$ and heat release $\leq H_2$, a metastable combustion results at B. The temperature $T_2$ is defined as the spontaneous minimum auto-ignition temperature. At a wall temperature $T_3 > T_2$, an uncontrolled reaction (an explosion) occurs. The theory of thermal explosions was developed by Semenov (6). Suppression of such an explosion requires that the suppressant must cool the reaction zone, or dilute fuel and/or oxidant, or both.

### 2.1.2. Chain Reaction Explosions

Combustion reactions, once initiated, proceed by a chain reaction mechanism. The system is initiated by the generation of free radicals, which are short lived, highly reactive atomic or molecular fragments. Each radical combines with a molecule of reactant to produce a product molecule, and another free radical, which then reacts with an adjacent reactant molecule so propagating the chain of events. This process continues until the propagating radical is involved in a reaction which does not liberate a second radical (a chain termination step) or until reactants are consumed.

A chain reaction may include a chain branching step; this is the production of more than one free radical, when a single radical reacts with a molecule of reactant. If chain branching occurs, the reaction will accelerate until the reactants are consumed. The heat liberated from the rapidly increasing number of propagating reactions will further accelerate the process.

The $\text{H}_2/\text{O}_2$ system shown below is an example of a branched chain reaction which illustrates the complexity of 'simple' combustion reaction systems.
\[ 2H_2 + O_2 \rightarrow 2H_2O \]

Chain Initiation
\[
\begin{align*}
    H_2 + O_2 & \rightarrow H_2O + \cdot O \\
    H_2 + O_2 & \rightarrow 2\cdot OH \\
    H_2 + O_2 & \rightarrow \cdot H + H\cdot O_2
\end{align*}
\]

Chain Propagation
\[
\begin{align*}
    \cdot OH + \cdot H & \rightarrow H_2O + \cdot H
\end{align*}
\]

Chain Branching
\[
\begin{align*}
    \cdot H + O_2 & \rightarrow \cdot OH + \cdot O \\
    \cdot O + H_2 & \rightarrow \cdot OH + \cdot H
\end{align*}
\]

Chain Termination
\[
\begin{align*}
    \cdot H + O_2 + N & \rightarrow H\cdot O_2 + N
\end{align*}
\]

Additional reactions which are of importance under certain conditions of temperature and pressure:
\[
\begin{align*}
    \cdot H + O_2 + H_2O_2 & \rightarrow H_2O + O_2 + \cdot OH \\
    \cdot H + O_2 + N & \rightarrow H\cdot O_2 + N \\
    H\cdot O_2 + H_2O_2 & \rightarrow H_2O + O_2 + \cdot OH \\
    H\cdot O_2 + H & \rightarrow H_2O_2 + \cdot H \\
    2H\cdot O_2 \xrightarrow{\text{wall}} & H_2O_2 + O_2 \\
    2H_2O_2 \xrightarrow{\text{wall}} & 2H_2O + O_2 \\
    H\cdot O_2 + N & \rightarrow 2\cdot OH + N \\
    & \text{or} \quad H_2O + \cdot O' + N
\end{align*}
\]

\( \text{(N - inert catalytic molecule)} \)

Suppression of chain reaction explosions can be achieved using an agent which acts as a free radical scavenger, thus inhibiting the chain propagation and chain branching reactions.
2.1.3. Actual Explosions

Most gaseous phase explosions propagate primarily by chain reaction mechanisms although thermal effects are important, whereas dust explosions are thought to be thermally controlled. In dust explosions, the combustion of the particulates may occur via chain reaction mechanisms, but the transfer of energy across the inter-particle voids is typically thermally controlled. Hence actual explosions cannot be categorised simply, and this must be taken into account when considering explosion suppression.

For a given system, the energy to activate the reaction $\Delta E$ and the thermal energy released $\Delta H$ can be represented as shown below:

![Energy Reaction Diagram]

The thermodynamic parameter, $\Delta H$, is a measure of the available chemical energy which will be liberated during combustion but the reaction will not occur unless the system is activated with an energy source greater than $\Delta E$. Systems with high activation energies, require energetic ignition sources to initiate an explosion. The thermodynamics of the reacting system define the energy released in an explosion, but the rate of propagation of the explosion is determined by the physical and chemical kinetics of the reacting system.
2.2. Explosions

2.2.1. Theory of Explosion Pressure Development

Campbell (7) demonstrated that it was possible to relate the burning velocity of a fuel/air mixture to the rate of production of gaseous reaction products by combining an elementary thermodynamic analysis with the velocity relationships at the combustion zone boundary. For a sphere with central ignition, he showed that the mass fraction burned is proportional to the cube of the elapsed time after the onset of combustion.

A detailed mathematical model of explosion development in a quiescent fuel/air mixture was proposed by Nagy et al. (8, 9). Both isothermal and adiabatic conditions were considered. The model assumed central ignition of the homogeneous fuel/air mixture. The explosion was considered to develop as a thin flame front, which represents the boundary between burned and unburned zones, and the pressure was assumed uniform throughout the vessel. The isothermal model assumed that the unburned and burned gas temperatures, \(T_u\) and \(T_b\), remain essentially constant, and resulted in an expression for the rate of pressure rise, \(dP/dt\), as a function of the initial, \(P_o\), and maximum, \(P_m\), pressures and the fundamental burning velocity \(S_u\):

\[
\frac{dP}{dt} \propto S_u \cdot \frac{P_m^{\frac{2}{3}}}{P_o^{\frac{1}{3}}} \cdot \left( \frac{P_m - P_o}{P} \right)^{\frac{1}{3}} \cdot \left( 1 - \frac{P_o}{P} \right)^{\frac{2}{3}} \cdot P
\]

Extension of the model to adiabatic conditions required the introduction of a factor which correlates \(S_u\) with \(P\). Such an adiabatic model of explosion pressure development resulted in better agreement with experiment than the isothermal model, but its increased complexity limited its applicability to well documented fuel/air systems. There are several other similar treatments of explosion development which are applicable to the initial
Consequences of a secondary dust explosion—5 lives lost
(Courtesy HMSO, London)
stages of explosion development where pressure can be assumed constant throughout the burned and unburned regions \((4,10-12)\). One analysis \((12)\) removes the requirement for an expression of the rate of flame spread and gives an equation which relates the pressure ratio in the explosion with the flame radius. More detailed theoretical treatments of explosion development have led to models which provide the foundation for the complete explosion history of a spatially homogeneous adiabatic system \((13,14)\). However, their general applicability is limited because detailed experimental data are not available for most fuel/air systems.

Turbulence was shown to have a major influence on the explosion severity of a combustible fuel/air mixture \((15-17)\), but the mechanism by which turbulence significantly increases the rate of flame propagation has not been fully elucidated. How \((18)\) considered that the increased burning rates observed in turbulent combustion systems involving particulate fuels are due to rapid mixing by eddy diffusion, and that the magnitude of the fluctuating velocity controlled the flame speed. Andrews et al. \((19)\) reviewed the theories of turbulence and concluded that the turbulent Reynolds number, \(R^\lambda\); of a combustible mixture is an important controlling parameter in turbulent flame propagation. He suggested that the ratio of the turbulent burning velocity to the laminar burning velocity was correlated with \(R^\lambda\).

Although comprehensive treatments of turbulent flame propagation have not been reported, particular relationships are established and form the basis for quantitative predictions \((20)\). Nagy's treatment \((9)\) is probably the simplest. He considered that turbulence distorts the spherical shell of the growing fireball and results in an increased burning velocity, \(\alpha' S_u\), relative to that of quiescent conditions.
2.2.2. Explosibility Scaling

The scaling of explosibility measurements has been largely based on a 'cube law' relation which is implicit in the theories discussed above. Hultmann (21) and Maisey (22) recognised that in theory the maximum explosion pressure is essentially vessel volume independent, and that the maximum rate of pressure rise can be scaled theoretically using a cube law relationship:

\[
\left( \frac{dP}{dt} \right)_{max_1} \cdot V_1^{\frac{1}{3}} = \left( \frac{dP}{dt} \right)_{max_2} \cdot V_2^{\frac{1}{3}} = K \text{ (constant)}
\]

where \( (dP/dt)_{max_1} \) is the maximum rate of pressure rise measured in volume \( V_1 \) and \( (dP/dt)_{max_2} \) is the maximum rate of pressure rise that would result in volume \( V_2 \). Bartknecht and Scholl (23-26) demonstrated experimentally that this relation is valid for gas explosions in volumes ranging from 1 dm\(^3\) to 20m\(^3\), and for dust explosions in volumes ranging from 1m\(^3\) to 60m\(^3\). However, these authors argue that dust explosibility measurements in volumes less than 1m\(^3\) give an underestimate of the actual explosion severity. Furthermore, work by Heinrich (27,28) suggested that in practice the measured final explosion pressure of dust explosions in small volumes is lower than that measured in larger volumes.

2.2.3. Dust Explosion Propagation

Many factors govern the propagation of flame in dust/air suspensions (29). No comprehensive investigation into the relative importance of, and interactions between, these factors has been reported; such evidence that exists is fragmentary and specific to particular dusts and experimental procedures. In consequence interpretation of data is confused and there is currently no unified understanding of combustion wave propagation in a dust/air suspension.
A comprehensive review of dust fire and explosion phenomena was published by Palmer in 1973 (30). The factors that influence flame propagation in a dust cloud were identified as:

(i) composition of dust and impurities;
(ii) homogeneity, mobility and turbulence of dust suspension;
(iii) concentration;
(iv) particle size and particle shape distributions;
(v) ambient temperature;
(vi) ambient pressure;
(vii) presence of inert and diluent gases;
(viii) moisture content of particulates;
(ix) presence of flammable gases and volatile species;
(x) the size and shape of the combustion chamber;
(xi) the nature and location of the ignition source.

The influence of both dust concentration and particle size on the resultant explosibility of specific dusts, particularly coal, is reported extensively (31-37). A definite lower explosibility limit (LEL) can be specified for a dust. As the dust concentration is increased above the LEL, the flame velocity increases to a broad maximum and subsequently decreases as the upper concentration limit is approached. The maximum flame velocity measured in dust/air suspensions usually occurs well above the stoichiometric concentration. There is a general trend for the explosibility of a dust to increase with decreasing particle size. However, an optimum particle size exists below which the explosion severity no longer increases as the particle size is reduced. This can be explained by postulating that smaller particles form agglomerates which behave as larger particles. Explosions develop in dusts of large particle sizes (typically > 100μm) only at high dust concentrations where the particle-particle separation is relatively small. The thermal mass of a larger particle acts to inhibit the
propagation of a combustion wave, thereby reducing the likelihood of an explosion. However, it is not possible to predict the maximum particle sizes of specific dusts at which explosions will or will not occur.

A theoretical model was developed for the prediction of the combustion rate of a cloud of dust with a defined particle size distribution (38, 39). The model was verified experimentally for anthracite, whose combustion rate is thought to be controlled by surface chemical reactivity. The mechanism by which a flame propagates through a dust suspension has not been established fully. Some dusts volatilise completely in the combustion zone whereas others partially pyrolyse. It is considered that heat transfer between the suspended particles is of fundamental importance to the mode of flame propagation.

Transfer of energy from the hot combustion wave surface to cold dust particles can be by conduction, convection, and/or radiation. Assuming that no chemical reaction occurs ahead of the combustion wave, a thermal model for the propagation of an explosion has been applied to dust suspensions (40, 41). The dust particles were considered to be heated by radiation and the interparticle voids by conduction. Rapid transfer of heat between the dust particles and air was assumed, thereby giving virtual temperature homogeneity. This theory related the burning velocity to temperature in a dust explosion, and gave higher values of burning velocity and temperature than were measured experimentally. The theory was extended (42) to account for a finite temperature difference between the particles and air, and to include a finite pre-ignition zone. The resultant analysis specified flame development by a pair of simultaneous differential equations. Since this treatment applied only to a plane wavefront propagating through a monodisperse homogeneous quiescent dust/air suspension its predictions cannot
be validated. However, the analysis was extended further by Bhadori. He included the influence of heat generated in the chemical reaction (43,44). It was found that experimental data reported by Howard (45) agreed well with Bhadori's predictions for coal dust. Cassel (46) has shown that radiative transfer of energy in dust flames is considerable, and Singer (47) has predicted the degree of radiant heating of coal dust particles ahead of the combustion wave from a numerical solution of approximate equations. The influence of radiative transfer is important to the course of a dust explosion.

The presence of inert particulates in a dust suspension was shown to reduce the burning velocity of the dust (48). Palmer (49,50) concluded that these inerts partially quench the combustion wave. He proposed a simple heat balance equation which enabled the amount of inert dust necessary to prevent flame propagation to be calculated. The validity of this approach supports the contention that flame propagation through a dust cloud is thermally controlled.

The criterion for ignition of dust suspensions is defined by a thermal ignition theory (51–54). For a monodisperse homogeneous system, the critical condition for ignition was derived. The size and energy density of a minimum ignition kernel for flame propagation away from the ignition source was established. The minimum ignition temperature was predicted to increase with particle size but to decrease with increasing dust concentration. The minimum ignition energies of dusts vary from 0.5mJ to 10kJ (55). Pellmont (56) has recently found that about 30% of dusts he tested have minimum ignition energies below 10mJ. The combustion of individual particles and droplets has been considered by many workers (20,57–63). For particulate combustion the first stage is radiant heating, emission and combustion of
volatiles, and the second stage is combustion of the solid residues. In the first stage, the particle is considered to be surrounded by a concentric diffusion flame and the rate controlling process is the diffusion of oxygen against the counterflow of combustion products. In the second stage, combustion is a reaction at the solid surface of the residue. This involves the following steps, any of which may be rate controlling:

(i) the transport of oxygen to the surface against the counterflow of combustion products;

(ii) chemical reaction at the particle surface, governed either by the involved chemical process or by adsorption kinetics;

(iii) transport of combustion products away from the surface.

The extent to which the two stages occur is specific to the material composition of the particle and to its area/volume ratio.

Although a basis for a theoretical understanding of gas explosions exists, the inherent problem with dust explosions is that they involve the combustion of a large number of particles which interact with each other. If the particular mechanism of flame propagation could be established with reasonable certainty for a specific dust then a theoretical analysis may be possible and useful for that dust type. However, its usefulness will fall a long way short of describing a 'real dust explosion' where the dust particles are of random geometry, inhomogenously distributed, and subject to turbulence. Experimental evidence of anomalous effects such as fragmentation of burning particles leading to burning solid or vapour being projected ahead of the combustion zone (64), further confounds fundamental modelling of explosion propagation in dust suspensions.
2.2.4. Dust Explosibility Measurement

The literature on the importance of dust explosibility characterisation is extensive (65–85). The explosibility parameters measured for dusts are:

(i) minimum ignition temperature;
(ii) minimum explosible concentration;
(iii) maximum explosion pressure, $P_{\text{max}}$;
(iv) maximum rate of pressure rise, $(dP/dt)_{\text{max}}$;
(v) minimum ignition energy;
(vi) maximum permissible oxygen concentration to prevent ignition.

The Hartmann vertical tube apparatus (86) was developed for dust explosibility measurement. In the United Kingdom, this apparatus has been the accepted means for explosible dust hazard assessment (65), and Hartmann data have formed the basis for the design of active explosion protection measures. Details of this standard test have been published by the Fire Research Station (87–89) and the US Bureau of Mines (90). Modifications to the basic design were reported by other workers (91, 92); however, the standard test is currently recognised by HM Factory Inspectorate as suitable for dust explosibility determinations.

The suitability of the Hartmann apparatus for meaningful dust explosibility measurement was questioned by Bartknecht (23, 24). He showed that, in the small volume of this test apparatus, a considerable underestimate of $(dP/dt)_{\text{max}}$ was obtained and that scaling of test results to larger volumes was not reliable. Bartknecht proposed a $1\text{m}^3$ explosion test apparatus, although this was no longer a laboratory test, and was thus very expensive.
All dust explosion test procedures require the formation of dust suspensions in closed vessels. Alternative methods of generating an effective dust suspension have been reported by Brown (93-95). Most test procedures disperse or eject the dust into the explosion vessel using compressed air. Ishihama (96) described a novel technique for dust dispersion in a 10 litre cylindrical test apparatus using the 'ball mill' principle.

The various alternative experimental test methods used to quantify dust explosibility have been reviewed (97). Beck (98) has summarised recently the current status of test methods in the Federal Republic of Germany. He states that in view of the difficulties in interpreting Hartmann test results all dusts must be evaluated in volumes $\geq 1\text{m}^3$. A standard $1\text{m}^3$ test apparatus and test procedure has evolved in Germany (99) and is now accepted throughout Central Europe. Eckhoff (100,101) suggested that one significant reason for the lower dust explosibilities measured in the Hartmann apparatus could be the lower turbulence levels, and argued that it would be advantageous to retain this apparatus as a standard because it was widely available and economic to use. He quantified the statistical scatter of Hartmann data and established empirical relations between recorded dust explosibility and the physical and chemical properties of a group of dusts. Burgoyne (102) also supported the retention of the Hartmann test procedure, in the absence of a better laboratory scale test method.

The fundamental limitations of the Hartmann test apparatus are appraised in this thesis, the author (103) has demonstrated the suitability of an alternative $43\text{dm}^3$ spherical test apparatus using a discrete ignition procedure. Lutoff (104) had described spherical explosion test apparatus also, but explosibility data commensurate with those achieved in volumes $\geq 1\text{m}^3$ were not demonstrated. Bartknecht (105) and Siwek (106) have described a $20\text{dm}^3$
spherical test apparatus that produced scalable dust explosibility data. Spherical test apparatus are gaining a measure of acceptance as alternatives to the Hartmann apparatus (107). The question of standard dust explosibility measurements has been reviewed by ISO/TC21/SC5/WG3. It is proposed (1) that the 1m$^3$ apparatus should be the accepted norm against which other test apparatus must be compared. Hence laboratory testing of dusts in the 20dm$^3$ and 43dm$^3$ apparatus, for example, will be acceptable; but the Hartmann test method will be rejected.

2.2.5. Explosion Test Results

Reported explosibility data for gases and dusts which were pertinent to this research are listed in this section (108).

2.2.5.1. Gas Explosibility Data

Table 2.1. presents the explosibility data of some quiescent flammable gas/air mixtures.

<table>
<thead>
<tr>
<th>FUEL</th>
<th>VOLUME m$^3$</th>
<th>CONCENTRATION vol%</th>
<th>$P_{\text{max}}$ MPa</th>
<th>$(dP/dt)_{\text{max}}$ MPa m s$^{-1}$</th>
<th>$K$ MPa m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>1</td>
<td>10</td>
<td>0.75</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>9</td>
<td>0.73</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>C$_3$H$_8$</td>
<td>0.001</td>
<td>4</td>
<td>0.70</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4</td>
<td>0.70</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>4</td>
<td>0.70</td>
<td>2.7</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4</td>
<td>0.70</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>70/30 CH$_4$/H$_2$</td>
<td>1</td>
<td>15</td>
<td>0.70</td>
<td>8.6</td>
<td>8.6</td>
</tr>
<tr>
<td>Town Gas</td>
<td>1</td>
<td>25</td>
<td>0.73</td>
<td>14.0</td>
<td>14.0</td>
</tr>
<tr>
<td>H$_2$</td>
<td>1</td>
<td>35</td>
<td>0.70</td>
<td>50.4</td>
<td>50.4</td>
</tr>
</tbody>
</table>

**TABLE 2.1**

nb: $K = \left( \frac{dP}{dt} \right)_{\text{max}} \cdot V^{\frac{1}{3}}$
2.2.5.2. Dust Explosibility Data

Table 2.2. presents $1m^3$ explosibility data of a range of industrial dusts.

<table>
<thead>
<tr>
<th>FUEL DUST</th>
<th>$P_{\text{max}}$</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC (particle size $\sim 14\mu$m)</td>
<td>0.85</td>
<td>5.0</td>
</tr>
<tr>
<td>Sugar</td>
<td>0.80</td>
<td>8.0</td>
</tr>
<tr>
<td>Coal</td>
<td>0.77</td>
<td>8.5</td>
</tr>
<tr>
<td>Polythene (particle size $\sim 80\mu$m)</td>
<td>0.92</td>
<td>11.5</td>
</tr>
<tr>
<td>Starch</td>
<td>0.94</td>
<td>13.6</td>
</tr>
<tr>
<td>Polythene (particle size $\sim 10\mu$m)</td>
<td>0.92</td>
<td>15.0</td>
</tr>
<tr>
<td>Cellulose</td>
<td>1.00</td>
<td>16.0</td>
</tr>
<tr>
<td>Dextrin</td>
<td>0.87</td>
<td>20.0</td>
</tr>
<tr>
<td>Organic pigment</td>
<td>1.00</td>
<td>28.6</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1.15</td>
<td>55.4</td>
</tr>
</tbody>
</table>

**TABLE 2.2.**

The turbulent dust explosibility data cover a similar range of $K$ values to those found for quiescent flammable gas/air mixtures. The German VDI (99) provides for a classification of dust explosion hazard based on $1m^3$ explosibility data:

<table>
<thead>
<tr>
<th>EXPLOSION CLASS</th>
<th>$K$ (MPa m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>St 1</td>
<td>0 to 20.0</td>
</tr>
<tr>
<td>St 2</td>
<td>20.0 to 30.0</td>
</tr>
<tr>
<td>St 3</td>
<td>30.0 →</td>
</tr>
</tbody>
</table>
It is considered generally that explosion suppression can be only applied to St 1 and St 2 dusts. The author (109) has appraised the problem of dust explosion hazard assessment, and concludes that an explosibility measurement is only one step towards hazard assessment, and that industrial processing conditions must be appraised in order that a more meaningful estimate of the explosion hazard of the worst case explosion in an industrial application can be made. This is discussed in more detail in section 6.1.5.

2.3. Explosion Suppressants

Literature pertaining to the suppression and extinguishment of flame was extensively reviewed by Fristrom (110) in 1967 (196 references) who surmised, that despite the effort and ingenuity that had gone into research of this area, a basic understanding of the action of suppressants was still in its formative stage. McHale (111) has published a survey of vapour phase chemical agents used for suppression of flame, which follows previous reviews by Friedman (112) and Skinner (113).

2.3.1. Modes of Suppression

The action of suppressants can effect one, or more, of the following:

**FUEL:** The fuel concentration can be lowered by dilution or smothering, or alternatively it can be increased such that fuel rich conditions are approached.

**OXIDANT:** The supply of oxygen to the combustion zone can be reduced by inerting, blanketing or smothering.

**TEMPERATURE:** The transfer of thermal energy can be reduced by insulation or cooling.

**COMBUSTION PROCESS:** The rate of reaction can be reduced by the presence of chemical inhibitors.
Thus physical mechanisms of suppression include separation of fuel and oxidant, dilution or enrichment of the explosible fuel concentration, and heat abstraction. Chemical mechanisms of suppression involve interference in the combustion reactions. Typically, smaller quantities of chemically active explosion suppressants are required, compared to physically active suppressants. Considerable controversy exists regarding the relative contributions of physical and chemical effects to the overall action of specific suppressants.

2.3.2. Halogenated Hydrocarbons (Halons)

Halons are used widely to inhibit and suppress combustion. The required minimum inhibiting concentration of various Halons are reported (114-120). The toxicity of unpyrolysed Halons has been the cause of much debate (121-123). The effectiveness and toxicity of some Halons are compared with a common inertisation agent, carbon dioxide, in Table 2.3.

<table>
<thead>
<tr>
<th>SUPPRESSANT</th>
<th>INHIBITING CONC.</th>
<th>TOXIC CONC. (onset of neurosis or cramp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide $\text{CO}_2$</td>
<td>30 Vol %</td>
<td>10-13 Vol %</td>
</tr>
<tr>
<td>Halon 1011 $\text{CCl}_3 \text{ BrH}_2$</td>
<td>8 Vol %</td>
<td>0.3 Vol %</td>
</tr>
<tr>
<td>Halon 1202 $\text{CF}_2 \text{ Br}_2$</td>
<td>4 Vol %</td>
<td>1.5 Vol %</td>
</tr>
<tr>
<td>Halon 1211 $\text{CF}_2 \text{ BrCl}$</td>
<td>4-6 Vol %</td>
<td>5.5 Vol %</td>
</tr>
<tr>
<td>Halon 1301 $\text{CF}_3 \text{ Br}$</td>
<td>3-6 Vol %</td>
<td>5-8 Vol %</td>
</tr>
<tr>
<td>Halon 2402 $\text{C}_2 \text{ F}_4 \text{ Br}_2$</td>
<td>1-2 Vol %</td>
<td>1.4 Vol %</td>
</tr>
</tbody>
</table>

**TABLE 2.3**

Halons act on the body primarily as anaesthetics, although some irreversible effects have been identified with certain agents.
From studies of the effectiveness of Halons as inhibitors of combustion (124 - 127) certain general features are noted:

(i) Halons containing Br and I are more effective than those containing F and Cl;

(ii) the presence of one atom of active halogen in a compound gives a marked increase in extinguishing effectiveness over a similar compound which contains none of that halogen. Adding a second atom of the same halogen produces only a marginal increase in effectiveness;

(iii) Halons are less effective inhibitors when added to the fuel side of the flame;

(iv) the effectiveness of a Halon is dependent on the fuel type and the Halon temperature.

2.3.2.1. Chemical Mechanisms

Most research has concentrated on comparative evaluations of the effectiveness of the various Halons. Measurements of ignition limits, flame blow off limits, and depression of burning velocity in the presence of low Halon concentrations have formed the basis of such studies.

Biordi's detailed investigation of flame structure (128 - 131) indicate that inhibition is a chemical effect. Consider the introduction of an organic halide RX into the flame reaction zone. The following two reactions occur to different degrees:-
Most opinion (132-140) supports a mechanism which involves the efficient competition of reactions such as:

\[
\begin{align*}
RX & \xrightarrow{\text{pyrolysis}} \hat{R} + \hat{X} \\
\hat{H} + RX & \longrightarrow \hat{R} + HX \\
\hat{H} + HX & \longrightarrow H_2 + \hat{X}
\end{align*}
\]

with the chain branching reaction:

\[
\hat{H} + O \longrightarrow \hat{O}H + \hat{O}
\]

Creitz (141) considered that Halons inhibit combustion by promoting recombination of reactive oxygen, but this hypothesis is largely disproved by Biordi's (138) work.

Wilson et al. (142,143) have demonstrated that the primary reaction zone of an inhibited flame is narrower and hotter than an uninhibited flame. The important inhibition reactions are considered to occur in the cool part of the flame prior to the primary combustion zone. Inhibition reactions have lower activation energies than the chain branching reactions and can effectively compete with the latter in the cooler portion of the flame. However, at higher temperatures the chain branching reactions will dominate resulting in rapid increase in radical concentrations. This interpretation suggests that:

(i) it is necessary to get the Halon suppressant into the pre-flame area;

(ii) the Halon must be sufficiently stable such that it acts faster than it decomposes.
It is possible that agent decomposition can explain the known failure of Halon to extinguish 'deep seated' fires although Fielding et. al (144) considered that this occurs because the Halon, whilst inhibiting the gas phase reaction, does not inhibit the gas/solid reactions \( C \rightarrow CO, CO_2 \) within the solid residue. Such reactions act to rekindle the combustion as the local Halon concentration decreases.

Fristrom proposed that a chemical inhibition parameter, \( \Phi \) (110), should be used to enable comparisons between the various experimental test methods. For burning velocity \( (S_u) \) measurements it is defined as:

\[
\Phi = \left[ \frac{O_2}{[\text{Halon}]} \right] \cdot \frac{\delta S_u}{S_u}
\]

where \( [O_2] \) = oxygen concentration and \( [\text{Halon}] \) = Halon concentration.

Inhibition effectiveness has been correlated with halogen content (134) and Fristrom (145) has recently shown that it is generally an additive function of the atomic composition of inhibitors:

\[
\Phi \propto \sum_x \Phi_x
\]

Since neither equilibrium, nor partial equilibrium changes in radical concentration and temperature were large enough to account for the effects of chemical inhibition, he surmised that inhibition is kinetically controlled, and developed a model whose predictions are consistent with the available inhibition data.

The question of whether charged species, known to exist in flames, are important in flame inhibition is unanswered. Spence and McHale (146) have calculated that the neutral inhibition reaction rates of Halon 1301 \( (CF_3Br) \)
on CH$_4$/air flames are more than two orders of magnitude larger than ionic inhibition rates, which suggests that ionic inhibition is insignificant.

As von Tiggelen points out (147) homogeneous gaseous phase inhibition of the type appraised above is not only by the substitution of the more reactive radicals by less reactive halogen atoms; but also by heat abstraction as a consequence of the presence of the inhibitor in the reaction system.

2.3.2.2. Physical Mechanisms

Larsen (148,149) proposed a physical interpretation of the mechanism of inhibition of Halons. Whilst accepting the evidence that halogenated agents enter into the chemistry of combustion, Larsen contended that this chemical reactivity was not the prime mechanism of inhibition. By conversion of the experimental data into a 'per weight' basis he showed that the relative effectiveness of halogens is in direct proportion to their atomic weights. He postulated that the primary role of the halogenated agents is similar to that of inert gases; that is they act as diluents and heat sinks without participating significantly in the exothermic combustion reactions. At very high temperatures, there is evidence that Halons can act as fuels (150), and it is in this role that Larsen suggests they participate in the flame chemistry. Larsen's observations can be interpreted as evidence for the existence of a limiting adiabatic flame temperature below which combustion cannot occur. A recent investigation by Tucker et. al (151) evaluated the relative importance of chemical inhibition and physical quenching in the extinction of diffusion flames by Halon 1301 (CF$_3$Br). Their results showed that chemical inhibition predominates only at low concentrations (<\(\frac{1}{3}\)Vol %) and that above this the Halon acts increasingly through its contribution to the heat capacity of the system.
2.3.3. Powders

Powders have gained increasing acceptance as alternatives to the established suppressants (152-154). Typical powder suppressants are based on:

- sodium bicarbonate $\text{Na H C0}_3$
- potassium bicarbonate $\text{K H C0}_3$
- sodium chloride $\text{Na Cl}$
- potassium chloride $\text{K Cl}$
- mono-ammonium phosphate $(\text{NH}_4)_2 \text{H P0}_4$
- potassium sulphate $\text{K}_2 \text{S0}_4$
- potassium cryolite $\text{K}_3 \text{Al F}_6$
- substituted urea Monnex

The effectiveness of certain powders to suppress combustion has been known for many years. The practice of spreading rock dust in coal mine galleries to render coal dust non exploisible is well established (155). The rock dust acts as an inert diluent and a heat sink. Dewitte et al (156) points out that the inhibition mechanism of powders can be classified also as physical or chemical. The extent to which the inhibition is homogeneous or heterogeneous is dependent both on the type of combustion and the mode of application of the powder suppressant. The suppressant particles may scavenge chain propagating species by surface adsorption or reaction, or they may vaporise in the combustion zone to produce gaseous products which participate in homogeneous inhibition reactions.

2.3.3.1. Homogeneous Suppression

Rossser, Inami and Wise (157) considered that the mechanism of inhibition by alkali metal salts involves the following steps:
(i) heating of particles by radiation and conduction;
(ii) evaporation of particles;
(iii) decomposition or reaction of the evaporated material to provide metal atoms;
(iv) inhibition of combustion by the metal atoms.

Iya, Wollowitz and Kaskan (158) reported a good correlation between the concentration of Na evaporated from two salts of various particle sizes, and the degree of inhibition. Kaskan (159) concluded from this and other work that such inhibition is predominately homogeneous. Friedman and Levi (160,161) showed that the presence of vapour phase elemental Na, alone, is insufficient to produce a detectable effect on a CH\textsubscript{4} diffusion flame. They suggest that reaction of chain propagating species (H, 0, O\textsubscript{H}) with the elemental alkali metal would proceed only by a three body collision process:

\[ \text{K} + \text{O\textsubscript{H}} + \text{M} \rightarrow \text{KOH} + \text{M} \]

and that the reaction with the hydroxide would be favoured.

\[ \text{KOH} + \text{H} \rightarrow \text{H}_{2}\text{O} + \text{K} \]
\[ \text{KOH} + \text{O\textsubscript{H}} \rightarrow \text{H}_{2}\text{O} + \text{KO} \]

As a rule, compounds containing potassium atoms are more effective than compounds containing sodium atoms. The suggestion that the alkali metal hydroxide is the inhibiting species explains the observation by numerous workers that oxygenated salts are more effective flame inhibitors than non-oxygenated salts, such as KCl (162). Tests by McHale (163) have shown that K\textsubscript{2}S\textsubscript{2}O\textsubscript{4}, KHC\textsubscript{3}O\textsubscript{3}, and K\textsubscript{2}C\textsubscript{2}O\textsubscript{4} inhibit combustion whereas KBF\textsubscript{4} does not. KOH is absent as a reaction species when KBF\textsubscript{4} is used to inhibit combustion;
thus KOH is the logical choice as the species largely responsible for homogeneous inhibition.

The high efficiency of the alkali oxalates is thought to be consequential on their rapid decomposition in the flame, and subsequent creation of submicron alkali carbonate particles. Birchall (164) postulates that inhibition by alkali metal salts is homogeneous, involving the volatilisation and reaction of these submicron particles to produce gaseous hydroxide as the inhibiting species. Monnex, a substituted urea, undergoes similar decrepitation as it passes into the hot combustion zone (165) although whether inhibition by these submicron particles is homogeneous or heterogeneous has not been resolved. However, this agent is claimed to be at least five times more effective than sodium bicarbonate.

Ammonium phosphate based powder suppressants are considered to inhibit via endothermic de-ammoniation and de-hydration reactions which cool the combustion zone:

\[
\begin{align*}
(NH_4)_2 H_2 P_0_4 &\rightarrow (NH_4)_2 P_0_4 + NH_3^+ \\
NH_4 H_2 P_0_4 &\rightarrow H_3 P_0_4 + NH_3^+ \\
2H_3 P_0_4 &\rightarrow H_4 P_2 O_7 + H_2 O^+ \\
2HP_0_3 &\rightarrow P_2 O_5 + H_2 O^+
\end{align*}
\]

Such agents can also act as chemical inhibitors:

\[
\begin{align*}
NH_3 + \cdot H &\rightarrow NH_4^+ \\
NH_4^+ + \cdot OH &\rightarrow NH_3 + H_2 O
\end{align*}
\]
2.3.3.2. Heterogeneous Suppression

Dolan et al. (165) showed that there was a direct relation between suppression efficiency and the surface area of powder suppressants, using CH$_4$/air flames, and thus concluded that chemical specificity and specific surface determine the effectiveness of powder suppressants. If the powder particles are sufficiently small, or exhibit a large specific surface they effect efficient heat abstraction. This conclusion was supported by Inami and Wise (166). Laffitte et al. (167) have evaluated the inhibition effectiveness of fine powders against various combustion systems ranging from laminar deflagration to detonation. Their work indicated that there is an optimum particle size for each type of combustion.

In a comparison of different powders the cryolites Na$_3$AlF$_6$ and K$_3$AlF$_6$ were found to be most effective (168). Cryolite particles have a ragged surface with numerous protrusions, and the higher specific surface is considered to account for the superior effectiveness of these agents. The observed influence of the physical characteristics of powder suppressant particles on the suppression effectiveness supports a significant heterogeneous mechanism. Such heterogeneous suppression may be physical or chemical.

2.3.4. Practical Applications

Experimental data can be misleading if referred to out of context, but it does provide a basis for adjudging the relative effectiveness of explosion suppressants. Hayes (169) reported that dry powder NaHCO$_3$ was about 20 times more effective than Halon and Milne (170) concluded that most of the recognised powder suppressants were more effective, on a weight basis, than Halon 1301. Bartknecht (108) has demonstrated that Halon 1011 can make an explosion more violent if it is delivered late into the growing fireball.
In practice, suppressant effectiveness is dependent on the nature of the explosion, the type of suppressant and the mode of application of the suppressant. Such factors as suppressant evaporation rate, suppressant decomposition rate, and thermal transfer efficiencies are dependent on the suppressor discharge characteristics and the residence time of the suppressant droplets/particles in the combustion zone. Hence the physical and chemical kinetics associated with the suppressant mechanism(s) play an important role in the effectiveness of an explosion suppression system.

2.4. Explosion Suppressors

An explosion suppressor is a device designed to rapidly inject suppressant into an industrial plant. The following performance requirements are essential for an effective explosion suppressor:

(i) rapid activation of device (no inertia);
(ii) rapid discharge of contents;
(iii) effective suppressant throw and dispersion.

Three types of explosion suppressors have been developed: hemispherical, cylindrical and high rate discharge (HRD) canisters. There is little published data on the discharge characteristics of explosion suppressors. Burgess (171) reports the measured spatial and temporal discharge profiles of a 76mm outlet diameter high rate discharge suppressor. The performance claims of the various manufacturers also provide some guide.

2.4.1. Hemispherical Suppressor

Plate IIa shows a sectioned hemispherical type explosion suppressor which can deliver liquid suppressant within 2ms of activation with a discharge velocity in excess of \(100 \text{ m s}^{-1}\). The hydraulic shock, which is generated by an electrically
b) HRD Suppressor-sectioned

a) Hemispherical Suppressor-sectioned

d) Explosively cut plate

c) Frangible disc

PLATE II
fired explosive charge in the centre of the liquid suppressant, 'petals' the scored frangible dome and thrusts the suppressant into the plant. This type of suppressor is marketed in capacities of 0.5, 1.0 and 5.0 dm$^3$. It is mounted inside the plant, and is therefore unsuited to high-temperature industrial processes. The hemispherical suppressor is exceptionally fast, but has a limited discharge range, typically $\approx 2.5$ m. It is particularly suited to ducting and small volume container applications.

2.4.2. Cylindrical Suppressor

This suppressor is based on a scored frangible cylinder which is operated in a mode similar to the hemispherical suppressor. Cylindrical suppressors discharge a 'wall' of suppressant into the plant, and are used for specific applications which necessitate this particular suppressant discharge profile (e.g. filters and drying ovens).

2.4.3. High Rate Discharge (HRD) Suppressors

High rate discharge (HRD) suppressors consist of a charge of liquid or powder suppressant contained in cylindrical or spherical canisters under a high pressure (2-12 MPa) of nitrogen. The canisters are fitted with explosively activated or pyrotechnically activated valves. HRD suppressors are marketed with outlet sizes of 19mm (single and double exits) and 76mm (single exits), and with suppressant capacities ranging from 3.5 to 70kg. Plate IIb shows one of the range of 76mm outlet HRD suppressors designed for the ejection of liquid suppressant. A frangible disc across the outlet orifice is ruptured by the hydraulic shock generated by an electrically fired detonator, and the suppressant is ejected from the canister by the compressed nitrogen. A 'pepper pot' spreader disperses the liquid as a fine mist into the plant. Plate IIc shows a ruptured 76mm diameter frangible disc. For powder suppressant the disc is replaced by a metal plate which is explosively cut using a shaped charge – see Plate IIId.
2.4.4. Suppressor Manufacturers

There are four major manufacturers of industrial explosion suppression systems:

(i) Total Foerstner & Co - BDR
(ii) Graviner Ltd - UK
(iii) Fenwal Inc - USA
(iv) Deugra Gmbh - BDR

The Total Foerstner explosion suppression systems are based on double exit (19mm diameter) HRD suppressors charged with ammonium phosphate powder suppressant. Graviner Ltd manufacture a range of hemispherical and HRD suppressors charged with liquid suppressant - water, Halon 1011 and Halon 1211. The range includes single and double exit 19mm diameter outlet HRD suppressors and single exit 76mm diameter HRD suppressors. Fenwal Inc originally manufactured Graviner type suppressors under license in the USA, and currently offer a similar range of suppressors. Deugra, a subsidiary of Graviner Ltd, manufacture both double exit (19mm diameter) and single exit (76mm diameter) HRD suppressors charged with ammonium phosphate powder suppressant.

2.5. Explosion Suppression

2.5.1. Historical Development of Explosion Suppression Techniques

In order to effectively suppress an explosion it is necessary to detect the developing explosion very quickly and then to inject suppressant rapidly into the industrial plant to suppress the enveloping fireball before destructive pressure is developed in the plant. A patent by Finch (172) in 1944 envisaged

* Powder suppressant – Furex 770
the explosion protection of grinders using photoelectric detection coupled with fast acting inerting and isolation. In 1948, Glendening and Macleennon (173) patented an explosion suppression procedure for the protection of both aircraft fuel tanks and industrial plant. Graviner Ltd received a development contract in 1952 (174) and demonstrated that aircraft fuel tank explosions could be suppressed effectively using either Halons or the fuel itself as the suppressant (175). A range of fast acting explosion suppression hardware was developed and was used to provide explosion protection of both fuel tanks and industrial plant. By 1959 (176), these systems had successfully suppressed or controlled some 35 industrial explosions, and had therefore demonstrated their effectiveness and value to industry. It was estimated recently (177) that the current worldwide distribution of automatic explosion control equipment exceeds 3800 installations, of which about 30% are in the United Kingdom.

2.5.2. Principles of Explosion Protection

Manufacturing and processing industries are required (178,179) to take all practical steps to prevent or restrict the propagation of explosions in industrial plant. Where it is not possible to prevent the formation of explosible dust or vapour clouds protection measures must be taken to minimise the consequence of an explosion incident. In principle, there are four alternative protection measures (180).

1) CONTAINMENT - Plant is constructed such that it is pressure resistant to the maximum explosion pressure.

2) INERTING - An inerting concentration of \( \text{N}_2 \) or \( \text{CO}_2 \) is maintained such that explosible conditions cannot occur.
3) VENTING – Weak vent panels are incorporated into the plant walls to relieve the explosion pressure into the environment.

4) SUPPRESSION – Explosion is detected and suppressed within the plant confines.

Venting is the least expensive option (181), but a large safe area is required adjacent to each and every vent since the full force of the explosion is released into the environment. The currently accepted procedure for scaling vent areas is provided by NFPA(182). Explosion suppression is fitted when it is impractical or unsafe to fit vents. Inerting and containment are self selecting for certain specialised applications.

2.5.3. Explosion Suppression Systems

Explosion detection by radiation is the preferred choice for solvent vapour and gaseous explosible hazards (183), whereas pressure detection is the usual choice for dust explosion hazards, because radiation from an incipient explosion may be obscured by the dust cloud. Typically, threshold pressure detectors are used, but a 'rate of rise' explosion detector is chosen for plants in which the normal pressure fluctuations may temporarily exceed the threshold level at which system activation is required.

There are a range of explosion suppressors currently available, see section 2.3. The most widely used suppressant in the UK is Halon 1011, although systems using Halon 1211, Halon 1301, water and ammonium phosphate powder suppressants are available. Descriptive details of explosion suppression equipment are provided by the various manufacturers, and numerous applications are described in the technical literature (184–202).
2.5.4. Explosion Suppression Tests

Reported experimental work on explosion suppression systems divides into three categories:

1) Coal Mine Trials - evaluation of the effectiveness of such procedures against mine explosions.

2) Plant Simulation Tests - determination of the viability of explosion suppression measures for specific industrial problems.

3) System Efficacy Tests - quantification of the performance limits of suppression systems in special test vessels.

Since this research has concentrated on the effectiveness of explosion suppression measures using hemispherical suppressors and the single exit 76mm diameter HRD suppressors, test results of significance using this hardware are included in Appendix 1 and are reviewed, with other results, below.

2.5.4.1. Coal Mine Tests

The major explosion hazard in coal mines is the ignition of methane at the coal cutting face, which can initiate a secondary coal dust explosion in the mine gallery. Krauchenko et al. (203) recently reviewed all test data on the effectiveness of systems designed to suppress incipient methane explosions, and thus reduce the risk of a subsequent dust explosion. This review indicated that powder suppressants, such as potassium carbonate, are most
effective for this purpose. To suppress fully developed coal dust explosions in mine galleries a 'triggered barrier' explosion suppression system has been developed. The propagating explosion is sensed and a barrier of suppressant is established in the mine gallery ahead of the flame front to inhibit the passage of the combustion wave. Triggered barriers using potassium bicarbonate, ammonium phosphate and water suppressants have proved effective (204-207).

Rae and Thompson (208) have shown that one single exit (76mm diameter) HRD suppressor charged with 1.75kg of Halon 1211 effectively inhibits a fully developed coal dust explosion in a 1.2m diameter tube. Tests by Liebmann and Richmond (209) have shown that two such suppressors charged with water can contain an explosion in a mine gallery, but that potassium bicarbonate is not effective when discharged from such suppressors. Triggered barriers can provide protection against dust explosions in pipes and ducts.

### 2.5.4.2. Plant Simulation Experiments

The first reported trials of explosion suppression systems refer to the original design aim of protecting explosions in aircraft fuel tanks (175). Tests with prototype 0.5 dm$^3$ hemispherical suppressors charged with Halon 104 demonstrated that petrol vapour cloud explosions in volumes ranging from 0.2m$^3$ to 2.3m$^3$ could be effectively suppressed. The efficacy of explosion suppression in aircraft fuel tanks was also demonstrated using Halon 1001, Halon 1011 and Halon 1202, although only the more volatile suppressants proved effective in low temperature trials. These early results provide evidence that the suppression of vapour phase explosions demands vapour phase inertisation of the unburned fuel/air mixture. The concept of aircraft fuel tank explosion protection was extended to provide protection of
refuelling tankers of volumes up to 12.7 m$^3$. A range of cylindrical suppressors was developed for this purpose, and their effectiveness demonstrated in a 3.6 m$^3$ vessel against stoichiometric propane/air explosions (210).

For most industrial applications, the effectiveness of explosion suppression measures is evaluated in experimental test vessels - see section 2.5.4.3. However, specific explosion suppression requirements have been evaluated using component parts of an industrial plant. Explosion suppression trials on a bag filter unit (211) have shown that a measure of protection is possible with the correct choice and combination of explosion suppressors, although the filter bags do impede the distribution of suppressant. Centrifuges, like filter units, present particular difficulties of suppressant dispersion. Containment of explosion pressure to below 20kPa has been demonstrated in a 0.9 m$^3$ centrifuge charged with stoichiometric butane/air mixture (212), and it is accepted (213) that explosion suppression is one means of providing protection for centrifuges.

Explosion suppression in fluid bed driers having volumes ranging from 0.3 m$^3$ to 6.3 m$^3$ has been demonstrated (214,215). Tests with the double exit (19mm diameter) HRD suppressors, and with the single exit (76mm diameter) HRD suppressors in a 1.7 m$^3$ fluid bed drier demonstrated both systems to be equally effective using an ammonium phosphate powder suppressant. A more detailed appraisal (216) of the single exit (76 mm diameter) HRD suppression system suggests that it can effectively contain dust explosions with an explosibility rate constant $K \leq 30$ MPa m s$^{-1}$ in fluid bed driers. Explosion protection of flare stacks has been experimentally demonstrated (217) using the principle of the triggered barrier described in 2.5.4.1. above. Such procedures have also been developed and tested for explosion protection of ducts (218). Recent tests indicate that large elevators can be adequately protected using the principle of explosion suppression (219).
Explosion Suppression trials in large volumes have been limited. Hillerbrand (220) fitted ten 5 dm$^3$ hemispherical suppressors charged with Halon 1001 in a 20 m$^3$ room. This system effectively suppressed a stochiometric propane/air explosion to a pressure$^+$ of ~1kPa using a detection pressure of 0.8 kPa, although the maximum recorded pressure was 6.8 kPa as a consequence of the final Halon vapour pressure. Fenwal (221) have shown that methane explosions can be suppressed to ~0.74 kPa in an 85 m$^3$ room using UV radiation detection and 35 dm$^3$ HRD suppressors charged with Halon 1211; it can be inferred (222) that such a system can be applied to aerosol filling rooms although the hazard of such rapid suppressant release to the operators is questionable. The US Coastguard have evaluated explosion suppression systems in the forward pump room of a tanker (223). This 517 m$^3$ room was partially filled (10% of total volume) with a propane/air mixture, and it was argued that this represented a real test since flame propagation beyond 10% of the total volume would represent a failed suppression. Tests using pressure threshold detection (detection pressure ~3.4 kPa) failed to suppress the explosion, whereas effective suppression was achieved using radiation detection and single exit (76mm diameter) HRD suppressors charged with Halon. The relative effectiveness of three Halons were assessed as: Halon 2402 > Halon 1301 > Halon 1211. Suppression of this large volume explosion was also achieved using potassium bicarbonate, but water was found to be ineffective.

2.5.4.3. Suppression System Efficacy Tests

The efficacy of explosion suppression measures against dust explosions has been shown in 1.9 m$^3$ spherical (224) and 1.13 m$^3$ cylindrical (225) vessels using pressure threshold detection and hemispherical suppressors. The original Graviner Halon explosion suppression system was evaluated by both

$^+$ the suppressed explosion pressure is the maximum pressure that results when an explosion is effectively suppressed.
the Bundesanstalt für Material Prüfung (226) and the Physich Technish Bundesanstalt (227). Both testing stations concluded that, in principle, such measures can provide protection against industrial explosions. The Deugra powder suppressant explosion suppression systems have been fully tested by the Bergbau-Versuchsstrasse, Dortmund (228). The efficacy of these systems was proven in these tests.

Bartknecht (23,24,108,229) has reported comprehensive determinations of the efficacy of explosion suppression measures against gas and dust explosions in 1m³ and 20m³ test vessels. He has reported that both the double outlet (19mm diameter) HRD suppression systems, and the single outlet (76mm diameter) HRD suppression systems can suppress gas explosion with explosibility ratings $K < 7.5 \text{ MPa m s}^{-1}$, and dust explosion with explosibility ratings $K < 30 \text{ MPa m s}^{-1}$ using a specific ammonium phosphate powder suppressant. His tests showed that there exists a wider margin of safety with the use of powder suppressants, as compared to that found with Halon suppressants. Furthermore, Bartknecht reports that more effective suppression is achieved with a higher nitrogen propelling agent pressure in the HRD suppressors. All tests were undertaken using relatively high detection pressure thresholds and Bartknecht's criteria of a successful suppression was a measured suppressed explosion overpressure of less than 0.1 MPa. In industrial practice, typical plant can only withstand overpressures of 0.02 - 0.03 MPa without distortion and rupture.

The author has suggested (230) that the impact of Bartknecht's thinking has led to two alternative philosophies of suppression system design and application:
(i) strengthen all plant to withstand an overpressure of 0.1 MPa and fit a 'standard' suppression system;

(ii) design an explosion suppression system for each application such that effective suppression is assured with all due consideration for processing parameters and plant component strengths.

Historically explosion suppression systems were tested against dust explosions of markedly lower turbulence than is currently the practice. The second philosophy of suppression system design requires that a more meaningful assessment of explosion hazard should be made than that based on an unquestioned dependence on some arbitrary test procedure; and the necessity to take account of the industrial processing conditions when designing explosion protection measures is being increasingly recognised (230 - 232).

A comparison of the relative performance of the double exit (19mm diameter) HRD suppression system and the single exit (76mm diameter) HRD suppression system has been completed and reported by Scholl (233) and Wiemann (234). They concluded that the single exit (76mm diameter) HRD suppression system provides a larger margin of safety for suppression system design. Comparative tests on a range of powder suppressants have shown that specific brands of ammonium phosphate based suppressants are the most effective (235,236).

The recent work of ISO/TC21/SC5/WG3 (see section 1.3) has determined the efficacy of explosion suppression measures based on both the double exit (19mm diameter) HRD suppression system and the single exit (76mm diameter) HRD suppression system against defined gas and dust explosions with the alternative suppressants: Halon 1011, water and ammonium phosphate powder (236 - 241).
3. THEORY

3.1. Explosions

An objective of this study of explosions was to define an unequivocal means of assessing an explosion hazard based on an explosibility measurement in a test apparatus. Hazard assessment is seen as the prediction of the pressure and fireball growth characteristics of the most explosible grade and concentration of material being processed in a particular industrial environment (specific conditions of temperature, pressure, humidity, turbulence, etc).

3.1.1. Explosion Development

After consideration of the published theories of explosion development, see section 2.2.1., it was concluded that the simple isothermal model proposed by Nagy et. al (8,9) could provide a foundation for the development of a mathematical model of explosion suppression.

Consider an explosion, centrally ignited and developing in a homogeneous fuel/air mixture within a closed vessel. Assuming isothermal equilibrated conditions, the explosion can be represented as a thin spherical combustion wave shell which separates the burned (b) and unburned (u) zones. At any time, t, the following quasi-static equations of state are assumed valid:

\[ P V_b = n_b R T_b \]  \hspace{1cm} (1)

\[ P V_u = n_u R T_u \]  \hspace{1cm} (2)

\[ m = n_u M_u + n_b M_b \]  \hspace{1cm} (3)

where m is the total mass of gas in the vessel and n and M are the number of moles and the mean molecular weight respectively.

* The terms 'explosible' and 'explosibility' refer to combustible materials which are liable to explode when dispersed as a mist or cloud in air. Explosive materials are specifically excluded.
The initial (o) and final (m) explosion states are therefore:

\[ P_0 V = \frac{m}{M_u} R T_o \]  \hspace{1cm} (4)

\[ P_m V = \frac{m}{M_b} R T_m \]  \hspace{1cm} (5)

and

\[ \frac{P_o}{P_m} = \frac{\frac{M_b}{M_u}}{\frac{M_b}{M_u}} = \frac{T_o}{T_m} = \frac{\frac{M_b}{M_u}}{\frac{T_u}{T_b}} \]  \hspace{1cm} (6)

Differentiating equation (2) gives:

\[ \frac{dV_u}{dt} = R T_u \frac{dn_u}{dt} \]  \hspace{1cm} (7)

\[ \frac{dV_u}{dt} = -A_b \frac{dr}{dt} = -A_b S_u \]  \hspace{1cm} (8)

where \( r \) is the flame radius at time \( t \), \( A_b \) is the flame area at time \( t \) and \( S_u \) is the fundamental burning velocity.

Note that the unconfined explosion flame speed \( S_f \) is given by:

\[ S_f = E S_u = \frac{T_b}{T_u} \cdot S_u \]  \hspace{1cm} (9)

where \( E \) is the thermal expansion factor of an ideal gas.

Differentiating equation (3) gives:

\[ \frac{dn_u}{dt} = -\frac{M_u}{M_b} \frac{dn_u}{dt} \]  \hspace{1cm} (10)
Adding equations (1) and (2) and differentiating gives:

\[
\frac{dP}{dt} = \frac{R}{V} \cdot \left( \frac{dn_b}{dt} \cdot T_b + \frac{dn_u}{dt} \cdot T_u \right)
\]  

(11)

Substituting equations (6) and (10) into equation (11) gives:

\[
\frac{dP}{dt} = \frac{R}{V} \cdot \left( \frac{M_u}{M_b} \cdot \frac{dn_u}{dt} \cdot T_u + \frac{dn_u}{dt} \cdot T_u \right)
\]

\[
\frac{dP}{dt} = \frac{R}{V} \frac{dn_u}{dt} \cdot T_u \cdot \left( 1 - \frac{P_m}{P_o} \right)
\]

\[
\frac{dP}{dt} = \frac{A}{P_o} \cdot \frac{S_u}{V} \cdot \left( P_m - P_o \right)
\]  

(12)

The flame radius, \( r \), can be calculated from equations (1-3) and (6)

\[
r^3 = a^3 \left( 1 - \frac{P_o}{P} \right) \left( 1 - \frac{P_o}{P_m} \right)
\]  

(13)

where \( a \) is the radius of a vessel of volume \( V \)

\[
hence \ V_b = V \left( 1 - \frac{P_o}{P} \right) \left( 1 - \frac{P_o}{P_m} \right)
\]  

(14)

Since \( A_b = 4 \pi r^2 \) and \( V_b = \frac{4}{3} \pi r^3 \)

\[
A_b = 4 \pi a^2 \cdot \left( \frac{3 V_b}{4 \pi a} \right)^{2/3} = A \left( \frac{V_b}{V} \right)^{2/3}
\]  

(15)

where \( A \) is the surface area of the test vessel.
Substitution of equations (14) and (15) into equation (12) yields the general expression:

$$\frac{dP}{dt} = S_u \frac{A}{V} \frac{P_m}{P_o} \left( P_m - P_o \right)^3 \left( 1 - \frac{P_o}{P} \right)^{3/2} P$$  \hspace{1cm} (16)

Note that a plot of $dP/dt$ against $(1 - P_o/P)^{3/2} P$ should give a straight line with a defined slope:

$$\text{slope} = S_u \frac{A}{V} \frac{P_m}{P_o} \left( P_m - P_o \right)^{3/2}$$  \hspace{1cm} (17)

Since $P_o$, $A$ and $V$ are known and $P_m$ can be calculated from the thermo-dynamics of the system, the burning velocity, $S_u$, can be determined. The measured maximum explosion pressure, $P_{\text{max}}$, is typically 10-20\% lower than the theoretically predicted maximum pressure, $P_m$, as a consequence of heat transfer to the test apparatus walls.

A computer programme was developed to permit the prediction of pressure and fireball radius as a function of time; this was for explosions of any fuel/air mixture with defined burning velocities and theoretical maximum pressures in vessels of known geometry and working pressure $P_o$. Since the flame speed, $S_f$, is slow relative to the speed of sound, pressure will equilibrate and the expansion of hot gases will ensure that the fireball assumes the approximate geometry of the vessel as it grows. Hence equation (16) is valid for both spherical and small aspect ratio vessels. For large aspect ratio vessels (ducts) wall quenching and pressure piling invalidates the application of the above arguments.

* The analysis neglects the influence of buoyancy which will distort the fireball shape.
The assumption of isothermally equilibrated conditions is obviously not strictly valid for an explosion event. However, agreement between theory and experiment, see section 6.1.6, is sufficiently good for the intended use of this model. The extension of the above theory to incorporate adiabatic terms, and perturbations on the fundamental burning velocity as pressure increases, may result in better agreement with experiment, but would confound the general applicability of the approach to essentially undefined fuels.

### 3.1.2. Turbulence

Although the exact influence of turbulence on explosion propagation is unknown, fuel/air perturbations with velocities greater than the flame speed must distort the flame front, and hence increase the rate of reaction. A simple conceptual explanation is that a turbulent burning velocity, \( \alpha S_u \), is defined as the sum of the quiescent burning velocity \( S_u \) and the average air perturbation velocity \( S_g \).

\[
\alpha S_u = S_u + S_g
\]

(18)

The turbulence factor, \( \alpha \), is an empirical measure of the influence of turbulence on the course of explosion propagation and \( S_g \) is a fundamental turbulence parameter representing some average of the combustion wave perturbations.

The explosion pressure, \( P \), at any time \( t \) is defined by the integral of equation (18), where \( S_u \) is replaced by \( \alpha S_u \).

\[
P = \int_0^t \alpha S_u \frac{A}{V} \frac{P_m}{P_o} \left( \frac{P_m - P_o}{P_o} \right) \left( 1 - \frac{P_o}{P} \right) \frac{3}{\sqrt[3]{\alpha}} \, P \, dt
\]

(19)
Since this simple model does not attempt to take account of the quenching influence of the vessel walls, the theoretical maximum rate of pressure rise, \( \frac{dP}{dt} \) occurs at \( P_m \).

Rearrangement of equation (6) shows that the maximum explosion pressure should increase linearly with an increase in the initial pressure, \( P_o \).

\[
P_m = \frac{\overline{M}_u}{\overline{M}_b} \frac{T_b}{T_u} P_o \tag{20}
\]

Substitution of equation (20) into equation (16) gives:

\[
\left( \frac{dP}{dt} \right)_m \propto P_o \tag{21}
\]

Hence both \( P_m \) and \( \frac{dP}{dt} \) are linear functions of the initial pressure, \( P_o \). Published data (108) supports this theoretical prediction.

An approximate estimate of the turbulence factor, inasmuch as it affects the measured explosibility parameter, \( \frac{dP}{dt} \) of an explosive fuel/air mixture can be defined thus:

\[
T_u = \frac{\left( \frac{dP}{dt} \right)_{\text{max}}}{\frac{1}{P_o}} \tag{22}
\]

Turbulent conditions

Quiescent conditions
3.1.3. Scaling and Interpretation of Explosion Data

The explosibility of a particular material is conventionally defined by the maximum pressure, \( P_{\text{max}}^* \), and the maximum rate of pressure rise, \( (dP/dt)_{\text{max}} \), measured with the most explosible fuel/air concentration in a standard test apparatus. The maximum pressure is essentially vessel volume independent whereas the maximum rate of pressure rise is a cubic function of vessel volume, see section 2.2.2.

\[
\left( \frac{dP}{dt} \right)_{\text{max}} \cdot V^{\frac{1}{3}} = K
\]

(23)

where \( K \) is the explosibility rate constant. Similarly, from a measurement of the time, \( t \), required to attain a certain pressure in a test volume, \( V \), the time, \( t_{x'} \), required to attain the same pressure in a volume, \( V_{x'} \), is given by:

\[
t_{x'} = \frac{V_{x'}}{V} \cdot \frac{1}{V^{\frac{1}{3}}} \cdot t
\]

(24)

Equations (16), (23) and (24) are self consistent.

In practice, non-central ignition and non-spherical geometry may result in a lower measurement of \( (dP/dt)_{\text{max}} \) because of the increased influence of wall quenching. Multiple ignition, however, will result in a more violent explosion. For a defined explosion hazard in a small aspect ratio vessel, the early part of the pressure/time characteristic is only influenced by the container geometry, whereas the later part of the pressure/time characteristic is influenced also by the surface topography and thermal characteristics of the vessel walls. From equation (16) the theoretical maximum rate of

* Note that \( P_{\text{max}}^* \) is conventionally recorded as gauge pressure.
pressure rise, \((dP/dt)_m\) occurs at the maximum pressure, \(P_m\). The experimentaly measured maximum rate of pressure rise, \((dP/dt)_{\text{max}}\), is dependent on the vessel wall quenching efficiency since it is related to the absolute pressure at which the slope of the pressure/time curve is measured, see diagram below:

Wall quenching will have less influence on a more violent explosion and more influence on a less violent explosion. Since a measurement of \(P_{\text{max}}\) is dependent on the relative rates of thermal energy released into the system and absorbed by the surroundings, it is influenced also by the explosion propagation and the wall quenching efficiency.

In conclusion, it must be recognised that the conventionally measured explosibility parameters, \(P_{\text{max}}\) and, \((dP/dt)_{\text{max}}\) are not absolute but dependent on the test apparatus. For a given explosible material, more meaningful explosibility parameters are the theoretical maximum explosion pressure, \(P_m\), and the fundamental burning velocity \(S_u\). The parameter, \(P_m\), can be calculated from the thermodynamics of the combustion system, see Appendix 2, and \(S_u\) can be determined from the early part of an experimental pressure/time record using equations (16) and (17).
Turbulence has a very significant influence on explosion severity, and must be taken account of when scaling explosibility data from test conditions to environmental conditions. The argument within section 3.1.2. supports the introduction of a turbulence factor, $\alpha$, into the cube law:

$$\frac{\left(\frac{dP}{dt}\right)_{\text{max}}}{\alpha} \cdot \frac{V^3}{\alpha} = K_q$$

where $K_q$ is defined as the explosibility rate constant specific to quiescent conditions. In practice, the turbulence factor, $T_u$, can be used as an approximation for $\alpha$.

### 3.1.4. Ignition Criteria

The criteria for the ignition of explosible fuel/air mixtures does not form part of this research. It is recognised that there exists a minimum size of ignition kernel for combustion to be self-sustaining, and thus for explosion to occur, and that a minimum ignition energy can be defined for each explosible material. The use of a high energy ignition source has the effect of truncating the theoretical pressure/time and fireball radius/time curves, see diagram below:

In a study of explosion suppression, the requirement is for reliable ignition with an ignition energy which is low relative to the explosion energy at detection of the incipient explosion.
3.2. Explosion Suppressants

It is evident from the literature, see section 2.3., that considerable controversy exists regarding the relative contributions of the physical and chemical aspects of inhibition, suppression and extinguishment by liquid and powder suppressants.

In industrial applications the choice of suppressant is influenced, not only by the effectiveness of the agent, but by such other factors as:

(i) toxicity;
(ii) contamination of the production line;
(iii) adverse reaction with product;
(iv) corrosiveness;
(v) post explosion inerting to restrict fire spread;
(vi) suitability of available suppressors;
(viii) cost.

The most widely used explosion suppressants are Halon 1011, Halon 1211, water and ammonium phosphate based powders.

3.2.1. Halons

Figure 1 presents published (114) peak flammability concentration data (defined as the minimum suppressant concentration required to inhibit combustion), against molecular weight for various vapour phase inhibitors in explosive n-heptane/air. The halogen based inhibitors have been broadly classified according to the largest halogen atom present in the molecule. It can be seen that:
(i) inhibition efficiency increases with molecular weight;
(ii) compounds containing Br and I are more effective than compounds containing Cl, which are themselves more effective than fluorocarbons and inorganic compounds;
(iii) differences between classes of compounds diminish with increasing molecular weight.

Figure 2 presents the same data plotted against the heat capacities (300°K) of the agents. The essential features of Figure 1 are reproduced which suggests two mechanisms of inhibition. A thermal heat sink effect, and superimposed over this is a chemical inhibition influence which is demonstrated by Br/I containing compounds, and to a lesser extent Cl containing compounds. Replotting the same data as a weight percent of agent basis, see Figure 3, shows that the weight effectiveness decreases with increasing molecular weight; the chemical influence of Br/I containing compounds still being in evidence. This analysis supports Larsen's contention (148,149) that Halons act as suppressants primarily through their contribution to the heat capacity of the system.

Thermal decomposition of the Halon is a conceivable first step towards chemical inhibition. From the kinetics of organic halide R-X bond fission (139) it can be inferred that the temperature requirement for significant Halon decomposition remote from the combustion wave exceeds the Halon autoignition temperature in the time scale appropriate to explosion suppression, see Figure 4. In the combustion zone Halon will be removed faster by reactions with H*, OH*, O2 and O*, since activation energies are typically 10-20 kJ, compared to ~300 kJ for R-X fission. Hence, thermal decomposition is unlikely to be a significant factor in explosion suppression. An evaluation of the kinetics of chemical inhibition of CH₄/air explosions by
Halon (242) has indicated that radical generation rates exceed radical destruction rates by a large factor in the combustion wave. Hence the suppression mechanism is not that of chemical inhibition of active radicals in the combustion zone, although such a mechanism is more viable in the case of turbulent explosions because of the increased flame area.

All evidence leads to the hypothesis that the suppression mechanism of Halons is predominantly physical. The experimental evidence for chemical inhibition is based on quasi-static experimental methods. In practice, the dynamic situation of a suppressed explosion event will enhance the relative importance of thermal quenching, indeed this must be the first step when a cold Halon spray enters the fireball. In consequence, chemical inhibition has been considered insignificant in the development of the mathematical model of suppression by Halons described in section 3.4.

The physical characteristics of some of the Halon suppressants are given in Table 3.1. Data for water are also included in this Table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Water</th>
<th>Halon 1011</th>
<th>Halon 1211</th>
<th>Halon 1301</th>
<th>Halon 2402</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight</td>
<td></td>
<td>18</td>
<td>129</td>
<td>165</td>
<td>149</td>
</tr>
<tr>
<td>Density (kg m$^{-3}$)</td>
<td>1000</td>
<td>1930</td>
<td>1830</td>
<td>1570</td>
<td>2180</td>
</tr>
<tr>
<td>Boiling temperature $T_B$ (K)</td>
<td>373</td>
<td>341</td>
<td>269</td>
<td>215</td>
<td>321</td>
</tr>
<tr>
<td>Autoignition temperature $T_e$ (K)</td>
<td>$\infty$</td>
<td>760</td>
<td>930</td>
<td>1000</td>
<td>840</td>
</tr>
<tr>
<td>Heat capacity - liquid $C_l$ (J g$^{-1}$ K$^{-1}$)</td>
<td>4.2</td>
<td>0.84</td>
<td>0.76</td>
<td>0.84</td>
<td>0.69</td>
</tr>
<tr>
<td>Heat capacity - vapour $C_g$ (J g$^{-1}$ K$^{-1}$)</td>
<td>180.</td>
<td>0.53</td>
<td>0.55</td>
<td>0.58</td>
<td>0.59</td>
</tr>
<tr>
<td>Latent heat of vaporisation $L$ (J g$^{-1}$)</td>
<td>2260</td>
<td>197</td>
<td>134</td>
<td>117</td>
<td>103</td>
</tr>
</tbody>
</table>

**TABLE 3.1.**
Since Halons can burn in air (150), their physical action as explosion suppressants must require that the Halon is not heated above its autoignition temperature. The maximum heat abstraction capability of a Halon is given by:

\[ H_e = C_1 (T_B - T_0) + L + \int_{T_B}^{T_e} C_g \, dt \]

(see section 3.4.)

If the fuel autoignition temperature is below the Halon autoignition temperature, a lower value of heat abstraction is attained. The relative thermal effectiveness of Halons 1211, 1301 and 2402, compared to Halon 1011, as suppressants of fuels with defined autoignition temperatures of 500°K and 1000°K respectively are summarised in Table 3.2.

<table>
<thead>
<tr>
<th>H_e ratio</th>
<th>(\phi = 500\text{ K} )</th>
<th>(\phi = 1000\text{ K} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1211 : 1011</td>
<td>0.77</td>
<td>1.12</td>
</tr>
<tr>
<td>1301 : 1011</td>
<td>0.74</td>
<td>1.15</td>
</tr>
<tr>
<td>2402 : 1011</td>
<td>0.70</td>
<td>0.93</td>
</tr>
</tbody>
</table>

**TABLE 3.2.**

Note that Halon 1011 is most effective against fuels with low autoignition temperatures, whereas Halon 1301 is most effective against fuels with high autoignition temperatures.
3.2.2. Water

The suppression mechanism of a water spray cloud can only be that of thermal quenching. Suppression is achieved if the rate of heat abstraction by the water suppressant exceeds the rate of heat generated by the exothermic combustion reactions. Thermodynamically, water is potentially the most effective liquid suppressant because of its very high latent heat of vaporisation, \( L = 2260 \text{Jg}^{-1} \); but in practice the physical kinetics of heat transfer reduces the relative effectiveness of this suppressant, see section 3.4.

3.2.3. Powders

The literature identifies the following contributory mechanisms to suppression of combustion by powders:

- **Physical**
  1. cooling of combustion products;
  2. heat abstraction from combustion wave;
  3. dilution and inertisation;

- **Chemical**
  1. homogeneous inhibition;
  2. heterogeneous inhibition.

This research considers only the suppression effectiveness of a mono-ammonium phosphate based powder suppressant (Firex 770). Spring (242) concluded from a study of the chemical kinetics of powder suppression that the maximum rate of surface radical recombination is always less than the rate of radical generation, and it is therefore unlikely that a chemical heterogeneous mechanism is dominant in powder suppression. Spring (242) further showed that homogeneous chemical inhibition is even less likely to contribute significantly to the suppression of explosions with powder. Since the inherent kinetic limitations of the chemical inhibition mechanisms are dependent on
radical generation and destruction rates, physical effects such as enhanced turbulence will not significantly affect these conclusions. The reported evidence (165) that the suppression effectiveness of powders is dependent critically upon the specific surface of the powder suppressant is not necessarily an argument for heterogeneous chemical inhibition since heat transfer rates will be dependent on the specific surface of the suppressant as well. The mechanism by which any powder suppresses combustion, therefore, is not established.

The minimum influence of the powder suppressant on a developing explosion must reflect its contribution to the thermal capacity of the system. Thus, the mathematical model of explosion suppression described in section 3.4 assumes that a powder suppressant acts only as a thermal quenching agent. In practice, any chemical inhibition will reflect an added benefit of this suppressant.

3.3. Explosion Suppressors

Hemispherical and High Rate Discharge (HRD) suppressors form the basis of most explosion suppression systems. This section considers the theory of suppressant discharge from such units. Plate II shows examples of sectioned suppressors used with liquid suppressant.

3.3.1. Hemispherical Suppressors

Consider the representation of a hemispherical suppressor shown below:

![Diagram of a hemispherical suppressor with a scored dome and detonator](image)

nb. suppressor is charged with liquid suppressant
When the explosive charge of the detonator is activated, a compression wave propagates through the liquid suppressant to the scored hemispherical dome. The resultant stress concentration causes the dome to split along the scored lines, and thus petal out releasing the suppressant. The hydraulic pressure resulting from the explosive device causes the liquid to break up into fine droplets as it is propelled into the plant.

The design of a hemispherical suppressor requires that the detonator(s) explosive energy should be more than sufficient to petal effectively the scored hemispherical dome, but should not cause fragments of the dome to tear off as it petals. Therefore, hemispherical suppressor design is a compromise between detonator energy, mechanical properties of the scored dome, and suppressor size. A higher explosive energy is required to discharge effectively suppressant from the larger hemispherical suppressors.

3.3.2. High Rate Discharge (HRD) Suppressors

The construction of a cylindrical high rate discharge (HRD) suppressor is shown below:
Rupture of the diaphragm results in the release of the liquid suppressant, which is propelled through the spreader assembly, and thus dispersed into the plant. Hydraulic shock created by the detonator causes the frangible diaphragm to rupture. This type of suppressor is only suitable for liquid suppressants. For powder suppressants the diaphragm is opened using a linear shaped explosive charge which is located around the periphery of the diaphragm.

The discharge characteristics of HRD type suppressors can be estimated using Bernouilli's equations of fluid flow, provided that the assumptions implicit in such an analysis remain valid.

Assumptions:

(i) suppressant is frictionless;

(ii) negligible turbulence occurs during discharge and flow can be considered streamline;

(iii) no significant 'punch through' of the propelling agent occurs;

(iv) the dynamic behaviour of fluid flow can be considered identical to that in the static case, i.e. constant head condition exists.

Assumptions (ii) and (iii), particularly, can only be considered reasonable for the initial stages of the discharge event. However, it is instructive to progress the analysis and compare with measurement.

Bernouilli's equation of streamline flow (243):

\[
\frac{P_1}{\rho} + \frac{1}{2} \cdot q_1^2 = \frac{P_2}{\rho} + \frac{1}{2} \cdot q_2^2 - gz \quad (26)
\]
where $\rho$ is the density of the suppressant.

\[
\text{since } \frac{P_2}{\rho} - gz \ll \frac{P_1}{\rho}
\]

\[
\frac{2P_1}{\rho} + q_1^2 \approx q_2^2
\]

\[
\frac{2P_1}{\rho} \approx q_2^2 - q_1^2 \approx q_2^2 \quad (\text{since } q_2 \gg q_1)
\]  

(27)

Hence, to a first approximation, the initial discharge velocity is given by

\[
q'_2 \approx \left(\frac{2P_1}{\rho}\right)^{\frac{1}{2}},
\]

which is independent of the outlet orifice area $A_2$. Note that the ullage, $v$, of the spreader (and elbow where appropriate) will result in a corresponding reduction in $P_1$:

\[
P_{N2} \cdot (V + v) = P_1 (V + v)^{\gamma}
\]

(28)

where $P_{N2}$ is the suppressant propelling agent pressure. Consider the adiabatic expansion of the propelling agent as the suppressant is discharged:

\[
P_{N2} (d-z'_o)^{\gamma} = P_1 (d-z)^{\gamma} \quad (\text{where } \gamma = \frac{c_p}{c_v})
\]

\[
P_1 = P_{N2} \cdot \left(\frac{d-z'_o}{d-z}\right)^{\gamma}
\]

(29)

Also

\[
q_2 = \frac{A_1}{A_2} \cdot q_1
\]

\[
q_2 = \frac{A_1}{A_2} \cdot \frac{dz}{dt} \quad (A_1 > A_2)
\]

(30)

Substitution of equations (29) and (30) into equation (27) gives:

\[
-\frac{dz}{dt} = \left[2 \left(\frac{A_2}{A_1}\right)^2 \frac{P_{N2} (d-z'_o)}{\rho (d-z)}\right]^{\frac{1}{2}}
\]

(31)
and the suppressant mass discharge rate is:

\[
\frac{dm}{dt} = -A_1 \rho \frac{dz}{dt} = \rho A_2 q_2
\]  

(32)

- note dependence on outlet orifice area \( A_2 \).

The area, \( A_2 \), is defined as the sum of the hole areas in the spreader. Figure 5 shows the theoretical and experimental depressurisation characteristics of a 76 mm diameter HRD suppressor with 76 mm spreader. It is evident that the theoretical and experimental curves are in good agreement for discharge times less than 15ms. However, beyond 70% depressurisation the theory predicts a more rapid discharge than is experimentally observed, and the predicted discharge time is grossly optimistic. This discrepancy reflects the breakdown of streamline flow conditions as the discharge event progresses.

Figure 6 shows the corresponding theoretical and experimental mass discharge characteristics, confirming that the above theory is only valid in the early stages of suppressant discharge.

3.3.3. Performance Analogues

From the results of suppressor discharge experiments described in section 5.3, a simple analogue of a HRD suppressor discharge characteristic can be defined, see section 6.3. The analogue has the form:

\[ \text{Mass Discharge Rate} \]

and is used as a basis for the model of suppression system performance described in section 3.4.

* Mensuration details are described in section 4.3.3.
3.4. Explosion Suppression

The experimental explosion suppression work reported in the thesis has concentrated on the four suppressants: Halon 1011, Halon 1211, water and mono-ammonium phosphate powder. The mathematical model of explosion suppression described below was developed to aid the design of suppression systems using the above suppressants. Its applicability to other suppressants has not been evaluated.

3.4.1. A Thermal Model of Suppression Effectiveness

In considering particular liquids as explosion suppressants, the first effect must be that of a cold finely dispersed liquid spray entering the combustion zone and extracting heat from the system. The observation, see section 3.2.1., that the Halon concentration required to render a flammable vapour/air mixture non-flammable is proportional to the Halon heat capacity, can be interpreted as evidence for the existence of a limiting adiabatic flame temperature, below which combustion reactions cannot self propagate. Hence, a thermal model of explosion suppression would require that the suppressant must cool the combustion zone to below this limiting temperature. Note that a particular property of Halons is that they will burn if they are heated sufficiently, see 3.2.2. above, and thus will compete with the fuel for the available oxygen. Hence for explosion suppression by Halon the suppressant must cool the combustion zone to below the fuel or Halon autoignition temperature, whichever is the lower.

This hypothesis identifies the need to deliver greater than a critical mass of suppressant into a given fireball of a developing explosion for it to be suppressed. The assumption implicit within this argument is that all of the suppressant droplets which enter the combustion zone effectively volatilise
and attain equilibrium temperature, i.e. the droplet residence time in the combustion zone is long relative to the rate of heat transfer. Failure of Halon droplets to extract sufficient energy from the combustion zone will result in an unsuppressed explosion in which the Halon may participate in the combustion chemistry.

The fractional consumption of fuel at time $t$ is given by $P_p - P_o / P_m - P_o$. Hence the heat energy released at time $t$ is:

$$Q_t = \frac{P - P_o}{P_m - P_o} \cdot Q_m$$ (33)

where $Q_m$ is the total heat energy released during the explosion. The energy that is consumed in cooling the combustion products to below the autoignition temperature, $T_e'$, of the fuel or of the Halon, whichever is the lower, is $Q_m - Q_e$ where $Q_e$ is the energy required to heat the system to a temperature $T_e$. Therefore the critical mass of suppressant, $M_t$, required in the fireball to lower the temperature of the reacting system to below $T_e'$, and hence to quench the explosion is given by:

$$M_t = \frac{Q_m - Q_e}{H_e} \left( \frac{P - P_o}{P_m - P_o} \right)$$ (34)

$Q_m$ and $Q_e$ are determined from the thermodynamics of the reacting system and $H_e$ is the energy absorbed by the suppressant in increasing from its initial temperature to $T_e'$ at constant volume.
where $C_l$ and $C_g$ are the specific heats of liquid and gaseous phase suppressant respectively, $L$ is the latent heat of vaporisation, $T_o$ is the initial temperature and $T_B$ is the liquid suppressant boiling point. This simple thermal model assumes that all of the suppressant droplets that enter the combustion zone are usefully 'consumed'. In practice, an efficiency term must be introduced which is a function of the suppressant evaporation rate, $\varphi$, in the combustion zone, see section 3.4.4.

3.4.2. Advanced Inerting

The thermal model described in 3.4.1. considers only the effect of a suppressant spray that has entered the fireball. However, suppressant in the unburned explosible mixture will have an influence on flame propagation. It is apparent from the reported peak flammability data that there exists a specific suppressant concentration that will render a particular explosible mixture non-flammable. Hence a suppressant has two effects, each of which must be satisfied if successful explosion suppression is to be achieved:

(i) extraction of thermal energy from the burned volume as described in 3.4.1. above;

(ii) advanced inerting, in which sufficient suppressant surrounds the combustion wave and inhibits further flame propagation.

Advanced inerting can be chemical or thermal, however, most evidence indicates that the predominant mechanism with both liquid and powder suppressants is thermal.
3.4.2.1. **Gaseous Phase Combustion**

For a gaseous explosible mixture advanced inerting can only be effective if the suppressant exists in the vapour phase as a homogeneous mixture with the unburned explosible constituents. Consider a combustion wave of radius \( r \) and thickness \( \delta r \). The mass of suppressant required to inhibit flame propagation, albeit momentarily, can be calculated assuming that the vapour phase suppressant has only to inhibit combustion at the combustion wave surface, but not extract energy from the burned volume.

\[
M_t = \frac{4\pi r^2 \delta r}{4/3 \pi r^3} \cdot \frac{Q_m - Q_\phi}{H_{\phi(g)}} \cdot \frac{1}{\gamma'} \cdot \frac{P - P_o}{P_m - P_o}
\]

where \( H_{\phi(g)} \) is the heat abstraction capability of the suppressant vapour and \( \gamma' \) represents the proportion of liquid phase suppressant evaporated in the unburned explosible mixture. Calculations indicate evaporation rates of \( \sim 1.5\% \) and \( \sim 0.1\% \) per 5ms for Halon 1011 and water suppressants respectively, when discharged into the unburned mixture, see Appendix 3. These calculations take account of the droplet size distribution of the suppressant spray discharge and forced convection, which results from the high discharge velocity of explosion suppressors.

3.4.2.2. **Particulate Combustion**

Flame propagation in most two phase dust/air explosible mixtures is dependent upon heat transfer between dust particles. Inerting is effected by both the liquid droplets/powder particles and the gaseous phase suppressant in the unburned explosible mixture. The liquid droplets/powder particles interfere with the propagation of the combustion wave because the dispersed droplets/particles, which are of similar size to the dust particles, occupy
interstitial positions between particles in the dust cloud. Hence, they interfere with the mechanism of flame propagation by absorbing energy from the combustion wave. Furthermore liquid suppressants may wet significantly the dust particles, and thus increase the requirement for thermal energy transfer, if a combustion wave is to be sustained. In all particulate combustion, where the mechanism of flame propagation is by heat transfer across the interparticle voids, the limiting condition for suppression is defined by equation 34.

3.4.3. Development of a Mathematical Model

The thermal model of suppression described above identifies both heat abstraction from the combustion zone and advanced inerting as complementary mechanisms of suppression. In fact, effective explosion suppression demands both sufficient heat abstraction and advanced inerting. In the absence of inerting, the explosion pressure will be reduced by the cooling of the gaseous products of combustion behind the combustion wave, but the flame will not be extinguished. If heat abstraction from the fireball is insufficient, the effectiveness of any inerting suppressant concentration is reduced and combustion may not be extinguished; higher inerting concentrations are required at elevated temperatures and pressures. In the particular case of Halon suppression this can result in complete failure to contain the explosion because the Halon can 'burn'.

A mathematical model of suppression has been developed, based on the theory described in 3.4.1 and 3.4.2 above. It uses a suppressant constant \( M \) as the basis for suppression criterion. For a given system, both heat abstraction and advanced inerting efficiencies can be compared on the basis of the concentration of suppressant, in kg m\(^{-3}\), required to contain effectively
a defined combustion wave of surface area $A_b$ and volume $V_b$.

\[
M_{\text{thermal}} = \frac{Q_m - Q_e}{H_e} \quad (37)
\]

\[
M_{\text{inerting}} = \frac{Q_m - Q_e}{H_e(g)} \cdot \mathcal{C}_r \cdot \frac{1}{V} \cdot \frac{A_b}{V_b} \quad (38)
\]

The larger the numerical value of $M$, the less effective is the chosen suppressant. Hence, for the given system, the larger value of $M_{\text{thermal}}$ or $M_{\text{inerting}}$ is used in the model since this larger value represents the limit of suppression effectiveness. Note that $\mathcal{C}_r$, $A_b$ and $V_b$ are all functions of pressure. The pressure/time curve of an unsuppressed explosion of a specific explosible mixture in a defined volume can be calculated from equation (19). Hence the mass requirement of suppressant as a function of time, $M_t$, is given by:

\[
M_t = M_{\text{thermal}} \cdot \frac{P - P_o}{P_m - P_o} \quad \ldots \quad M_{\text{thermal}} \geq M_{\text{inerting}} \quad (39)
\]

\[
M_t = M_{\text{inerting}} \cdot \frac{P - P_o}{P_m - P_o} \quad \ldots \quad M_{\text{inerting}} > M_{\text{thermal}} \quad (40)
\]

Superposition of the suppressant discharge characteristic onto the suppressant requirement characteristic enables the suppressed explosion time, $t_{\text{RED}}$, and hence the suppressed explosion pressure, $P_{\text{RED}}$, to be estimated. It is possible to envisage three alternative outcomes from such an analysis, see diagram below.

![Diagram showing three scenarios of suppression: Reliable Suppression, Unreliable Suppression, Failed Suppression.](image-url)
A failed suppression will be predicted, if the suppressant is delivered into the fireball too late, too slowly, or in insufficient quantity. These three modes of failure are illustrated below:

Note that the above analysis refers to the conditions prevailing within and at the surface of the fireball. The suppressant delivery characteristic of each type of explosion suppressor is defined by its theoretical analogue, see section 3.3.3. However, the mass influx of suppressant into the growing fireball is dependent on fireball location and its capture cross-section in relation to the suppressor(s) location(s). In real situations, the location of a developing explosion is unknown. Also most explosions are turbulent, localised air flow velocities exceed the flame speed and the calculated fireball radius has no direct physical significance.

Since the prime objective of developing a mathematical model of suppression effectiveness is to provide a 'tool' to assist in the design of explosion suppression systems, the model must relate to the real industrial problem. A propagating explosion exists at some location within the defined volume, either, as a fireball or as tongues of flame propagating away from the source of ignition. The suppressant mass requirement can be redefined so that the total suppressant concentration within the container is such that the critical mass requirement \( M_t \) is available at the combustion zone — see below:
This assumes that the suppressant is effectively and evenly dispersed throughout the total container volume.

3.4.4. The Model

The values of the suppressant constants, \( M(\text{thermal}) \) and \( M(\text{inerting}) \), are calculated. The value of \( \gamma \) is chosen as that corresponding to the detection pressure \( P_A \), see Appendix 3. This choice of \( \gamma \) will result in a small underestimate of the effectiveness of the suppressant as an advanced inerting agent. The largest value of \( M(\text{thermal}) \) or \( M(\text{inerting}) \) is assigned as the suppressant constant \( M \) in the model.

Figure 7 shows a nomogram which outlines the logistics of this model of explosion suppression for a specific suppression system \((V = 1 \text{ m}^3, \text{ one } 3 \text{ dm}^3 \text{ capacity HRD suppressor})\). The pressure/time curve of an unsuppressed explosion of the specific explosible mixture in the defined volume is calculated from equation (19). The suppressant mass requirement in the volume \( V \) is given by:

\[
M_t \cdot \frac{V}{V_b} = M \cdot \frac{P - P_0}{P_m - P_0} \cdot \frac{V}{V_b} \quad (V_b > 0) \quad (41)
\]

The detection pressure of the explosion suppression system, \( P_A \), defines a corresponding time from ignition, \( t_A \). However, since pressure equals the speed of sound \((330 \text{ m s}^{-1})\) a small delay will occur between the attainment of the pressure \( P_A \) at the combustion wave surface and detection of this pressure at the vessel wall. This delay, \( t_{\epsilon} \), is estimated by:

\[
t_{\epsilon} = \frac{a}{330}
\]

where \( a \) is the nominal radius of the vessel in metres. Hence, in effect, the explosion is detected after time:

\[
t_{A}' = t_A + t_{\epsilon}.
\]
The discharge characteristic of each suppressor in the explosion suppression installation being modelled is defined by its corresponding theoretical analogue, see section 3.3.3. For multiple suppressor systems, the discharge characteristics are considered additive on their appropriate time bases.

Suppressant arrives at the spreader(s) after time interval, $t_B$ (see Figure 7). The time interval, $t_c$, is defined as the time necessary for the fireball to be completely enveloped in suppressant, and is determined from the appropriate suppressor discharge characteristics as follows:

(i) for experiments, in which central ignition of quiescent explosible mixtures is assumed, $t_c$ is determined by superposition of the suppressant discharge characteristic onto the fireball growth characteristic as shown in the example of Figure 7. Here, $t_c$, is defined as the time taken for the front lobe of the suppressant to reach the extremity of the fireball surface;

(ii) for experiments and applications using only a single suppressor involving turbulent explosions and/or non-central ignition $t_c$ is defined as the time interval necessary for the suppressant front lobe to reach the extremity of the container;

(iii) for experiments and applications in which two or more suppressors are fitted to the container, and turbulent explosions are assumed, $t_c$ is defined as the time interval necessary for the suppressant front lobe to reach the geometric centre of the container. (Note that criterion (ii) is applied if all suppressors are located on only one side of the container).
Hence, the time at which the suppressant is assumed to have started just to influence the growing fireball in this model is given by $t_A + t_B + t_C$. This worst case time is taken as the starting time for the mass influx of suppressant into the combustion zone. The intersection of the suppressor(s) mass discharge characteristic with the calculated suppressant mass requirement characteristic, as determined by equation 41, defines a suppressed explosion time, $t_R$, and hence the suppressed explosion pressure, $P_R$, for the system.

The quasistatic thermodynamic model takes no account of the physical kinetics of the explosion suppression event. It contains the implicit assumption that the rate of thermal transfer of energy as the liquid suppressant droplets penetrate the fireball is fast, relative to the suppressed explosion event. Droplet vaporisation rates, based on the theoretical droplet size distribution of standard HRD suppressors, determine the suppressant thermal transfer efficiency $\phi$, see Appendix 3. $\phi$ increases with increasing vessel volume because of the increased residence time of suppressant droplets in the combustion zone. Increased suppressant discharge velocity (i.e. higher suppressant propelling agent pressure) has only a small influence on $\phi$ because the increase in evaporation rate which results from the higher level of forced convection is offset by the reduced residence time in the combustion zone. Typical thermal transfer efficiencies of Halon 1011 and water suppressant in a 1m$^3$ container are 90% and 50% respectively.

The effective suppressor discharge characteristic, as defined by the suppressor theoretical analogue, see section 3.3.3, is attenuated by the calculated thermal transfer efficiency $\phi$. Droplet vaporisation rate is considered to be the rate determining step in the kinetics of the action of liquid suppressants, and therefore a 'worst case' prediction of suppression system effectiveness must include a meaningful estimate of the thermal transfer efficiency, $\phi$, for the system in question.
To facilitate a routine evaluation of suppression system applications, this model was structured into a computer programme. The programme was structured as a versatile tool for both continuing explosion suppression research, and for system evaluation.

3.4.5. The Computer Programme

The following input data are required for the computer assessment of an explosion suppression system.

Vessel volume - $V$
Vessel surface area - $A$
Theoretical maximum explosion pressure - $P_m$
Initial pressure - $P_0$
Fundamental burning velocity - $S_u$
Nature of process - turbulence estimate $\alpha$ or $T_u$
Number and type of explosion suppressors
Type of suppressant
Charge and propelling agent pressure of suppressors
Suppressant constant - $M$ (thermal) or $M$ (inerting), whichever is the largest
Detection pressure threshold - $P_A$
Suppression system thermal transfer efficiency - $\eta$

Optionally it is possible to 'override' the calculated value of suppressant throw or time interval $t_C$ with input data. Multiple suppressor configurations can be accessed, providing that all suppressors contain the same suppressant.
The assumptions of the mathematical model all err on the side of safety. However, it is essential that a system which is borderline between suppressing and failing to suppress the explosion is readily identified. As an 'a priori' judgement of safety a suppression system is only considered viable if the following conditions are satisfied.

(i) the suppressant delivery rate exceeds the suppressant requirement rate, at suppression, by a factor greater than two;

(ii) the mass of suppressant delivered exceeds the mass of suppressant required, at suppression, by more than 50%.

The programme provides a prediction of the system suppressed explosion overpressure, together with an assessment of the reliability of the proposed suppression system. Optionally the programme can provide graphical output of pressure versus time, fireball radius versus time, suppressant requirement versus time and suppressant delivery versus time for the modelled system. An example of the computer output is shown in Figure 8.
4. EXPERIMENTAL METHODS

4.1. Explosions

4.1.1. Explosion Test Apparatus

Measurements of the explosion violence of combustible gas/air and dust/air mixtures were undertaken in both laboratory and large scale test vessels. Tests in a Bartknecht 1m$^3$ apparatus were carried out at Bergbau Versuchsstrecke, Dortmund in collaboration with Dr Scholl (see section 1.3.1). A standard Hartmann vertical tube apparatus, and experimental explosion test apparatus were constructed specifically for this research.

'Standard' Test Apparatus:

(i) Bartknecht 1m$^3$ vessel;
(ii) Hartmann Tube.

'Experimental' Test Apparatus:

(i) 1:1 aspect ratio vertical tube apparatus;
(ii) 43 dm$^3$ spherical apparatus;
(iii) 6.2 m$^3$ IEP test apparatus.

4.1.1.1. 'Standard' Bartknecht 1m$^3$ Vessel

The Bartknecht apparatus is shown in Plate III. The explosion chamber has a nominal volume of 1m$^3$ and a 1:1 aspect ratio.

To determine the explosibility of gases the fuel/air mixture is metered into the chamber, sampled and analysed to ensure that the required fuel concentration has been attained. The explosion is initiated by an induction coil spark across a 4mm spark gap in the centre of the chamber and the resultant
PLATE III: Bartknecht 1m³ Explosion Test Vessel
pressure/time history monitored using a pressure transducer and U.V. oscillograph recorder.

To determine the explosibility of dusts, a known weight of the dust sample is placed into a 5.4 dm$^3$ canister, which is pressurised to 2MPa with compressed air. The canister is fitted with an electrically activated pyrotechnic valve. When the valve is activated the dust sample is transported by the compressed air and dispersed uniformly in the chamber by a spray ring. The resultant turbulent dust suspension is ignited centrally with a 10 kJ pyrotechnic igniter, which is activated 0.6s after the pyrotechnic valve has been activated. This ignition delay is chosen because 0.6s is the time required to disperse effectively all of the dust sample into the explosion chamber.

4.1.1.2. 'Standard' Hartmann Vertical Tube Apparatus

A Hartmann vertical tube apparatus was constructed to the specification given in drawings supplied by the Fire Research Station, Borehamwood. This apparatus, see Plate IV, has an internal volume of $1.23 \text{ dm}^3$ and an aspect ratio of 4.6:1.

A weighed sample of dust is heaped into the bottom cup and the small air reservoir (0.05 dm$^3$) is charged with compressed air to a pressure of 0.82 MPa. A solenoid valve releases this compressed air charge, via a mushroom deflector, onto the dust, which is itself then effectively dispersed upwards onto the ignition source. Two alternative ignition sources can be used:

(i) train of induction coil sparks – 100 Hz;
(ii) electrically heated coil.
PLATE IV: Hartmann Vertical Tube Apparatus

PLATE V: 1:1 Aspect Ratio Vertical Tube Apparatus
The accepted mode of operation requires that the ignition source should be switched on before the solenoid valve is activated.

4.1.1.3. 'Experimental' 1:1 Aspect Ratio Vertical Tube Apparatus

This apparatus was designed and constructed to investigate the influence of aspect ratio on the measured explosion parameters in the Hartmann tube. It consists of a 1.75 dm³ 1:1 aspect ratio explosion tube which was mounted on the standard Hartmann dust dispersion system, see Plate V. Provision was made for spark ignition across central electrodes.

4.1.1.4. 'Experimental' 43 dm³ Spherical Test Apparatus

This apparatus, see Plate VI, was designed with the specific objective of seeking to establish a laboratory scale test procedure that would produce dust explosibility results comparable with results obtained in the Bartknecht 1m³ apparatus. It was designed around an available stainless steel pressure vessel which had a hydraulic test pressure of 4 MPa.

A 1.8 dm³ dust dispersion canister was fitted to the prototype apparatus. This represented the same air reservoir to explosion chamber volume ratio as that used in the Hartmann apparatus. However, the final design of the 43 dm³ apparatus used a 0.9 dm³ dust dispersion canister pressurised to 1.64 MPa, because this higher pressure reduced the time required to effectively disperse the dust into the explosion chamber. The experimental apparatus had the facility to spray the dust into the chamber using either a pepper pot spreader or a hemispherical spray ring. The pepper pot spreader was an 18mm diameter hemisphere drilled with seven 4mm diameter holes. It was located in the top of the spherical explosion chamber. The hemispherical spray ring was constructed from 12mm diameter copper pipe.
PLATE VI: 43 dm³ Spherical Explosion Test Apparatus
It was drilled with three rows of 2mm diameter holes staggered within a 120° segment. The spray ring, which was also mounted from the top of the vessel had a radius of 180mm.

Provision was made for two alternative ignition sources:

(i) train of induction coil sparks - 100 Hz;
(ii) high energy capacitive discharge.

All tests were undertaken with central ignition. Since the 43 dm³ test apparatus was not constructed to rigorous pressure vessel standards it was tested hydraulically only to a pressure of 2 MPa and was located within a thick walled concrete block house. All explosion tests were undertaken remotely, and safety interlocks ensured that the block house could not be entered whilst the ignition source was enabled.

4.1.1.5. 'Experimental' 6.2 m³ IEP Test Facility

A 6.2 m³ explosion suppression test facility was set up as part of the project. This had an aspect ratio of 1.75:1 and could also be used for unsuppressed gas and dust explosion trials. Provision was made for central ignition by either induction or high energy capacitive spark. A detailed description of this test facility is provided in section 4.5.

4.1.2. Ignition Sources

4.1.2.1. Standard Ignition Procedures

The standard ignition procedures divide into two categories:

(i) sustained - a) hot coil;
    b) train of induction sparks;
    (these are typically used with the Hartmann Apparatus)

(ii) discrete - 10kJ pyrotechnic igniter;
    (this is used with the 1m³ test apparatus).
The standard hot coil is five turns (8mm dia) of 18SWG Ni/Cr wire heated to a surface temperature which exceeds 750°C by a 10V, 8A power supply. The train of induction coil sparks are obtained using a Rühmkoff coil which has an 80W input energy. An 8mm spark gap between pointed electrodes is used typically. This apparatus provides one $\sim \frac{1}{2}$J induction coil spark every 10ms.

The standard 10kJ pyrotechnic igniter consists of two 1.2g pellets of the following composition:

\[
\text{zirconium metal powder} \\
\text{barium nitrate} \\
\text{barium peroxide} \quad \{ \text{manufactured by Sobbe, W. Germany} \}
\]

It produces a dumb-bell shaped ignition kernel which extends some 200mm from the pellets. The burning time of this ignition source is $\sim 40$ms.

4.1.2.2. Experimental Ignition Procedures

In addition to the standard ignition procedures described above, experimental work reported in this thesis was undertaken using the following ignition procedures:

(i) a train of induction coil sparks provided by a Rühmkoff coil activated after a preset ignition delay;

(ii) an induction coil spark (30mJ) provided by a vehicle ignition coil (This was used as an alternative to the Rühmkoff coil in the 6.2 m$^3$ vessel because the latter was intolerant of atmospheric humidity);
(iii) a high energy capacitive spark specifically developed for this research, see section 4.1.2.3.;

(iv) a standard fuse head igniter;

(v) a 1kJ pyrotechnic igniter (1:1 aluminium powder : potassium perchlorate).

For turbulent gas and dust explosion experiments the igniting sources were all activated at a predetermined time delay, $t'_v$, after the activation of the gas or dust dispersion procedure. It can happen that the actual ignition delay, $t_v$, is greater than this preset ignition delay with ignition using the train of induction coil sparks. The actual ignition delay, $t_v$, corresponds to a particular level of turbulence at which ignition results.

4.1.2.3. Development of a High Energy Capacitive Discharge Ignition Source

The 10kJ pyrotechnic igniter used in the $1\text{m}^3$ Bartknecht apparatus has proved an effective igniter of dust clouds. However, the extensive fireball produced by the pyrotechnic, could mask the effectiveness of an explosion suppression system. It has been suggested (244) that the ignition energy of such a device represents a significant proportion of the total system energy in an explosion suppression trial with a sensitive suppression system. Indeed it is possible to detect and contain an explosion in the $1\text{m}^3$ vessel before the explosion energy exceeds 40kJ. For this reason the development of an alternative high energy discrete ignition source was considered essential.
The chosen ignition source was a capacitive discharge between electrodes of defined geometry and separation. Since it was a pre-requisite that this capacitive discharge could be triggered at a defined instant in time, a three electrode configuration was developed. A spark from a standard motor vehicle induction coil was used to trigger the discharge across the main electrode spark gap. This triggered discharge was particularly attractive because it avoided the use of very high voltage levels, and the requirement to switch high current levels. The 'a priori' aim of the designed ignition source was to deliver an ignition energy of 100J. A 40μF rapid discharge capacitor charged to 2.25 kV was chosen. This type of ignition procedure is not suitable for metal dusts, or any highly conductive dust clouds. The experimental apparatus, see Plate VII, was constructed so that capacitive discharge energies \((\frac{1}{2} CV^2)\) of 50 - 500J could be achieved using the 40μF capacitor, and provision was made to substitute alternative capacitors to extend its working range. The leads between the capacitor and the electrodes were kept as short as possible and constructed from high current low loss cable. An analysis of the discharge characteristics of a 100J capacitive spark energy using a high resolution storage oscilloscope shows that the discharge is oscillatory with \(\sim 50\%\) of the net energy being released in the first cycle of duration \(\sim 1\mu s\). The oscillatory discharge is sustained for \(\sim 250\mu s\).

* It is accepted that a significant proportion of this calculated energy will be quenched by the electrodes.
4.1.3. **Control Unit**

The design of the control electronics for the unsuppressed explosion experiments undertaken in the various test vessels was conditioned by two specific requirements:

(i) the control unit should be sufficiently versatile to accommodate tests of quiescent gas explosions and turbulent gas and dust explosions for the different ignition procedures described above in both small and large test vessels;

(ii) explosion testing should be undertaken in a safe, foolproof, and approved manner.

It was required further that the control unit could be used, together with auxiliary circuitry, for explosion suppression trials. The control unit was required to start and stop the chart drive of the U.V. recorder, which provided the pressure/time history of the explosion event, and to provide 'event' signals to the recorder as appropriate. The following control sequence was defined:

+ It was necessary to satisfy the Company safety officer that sufficient consideration had been given to safety before explosion tests were authorised.
START

U.V. recorder chart drive switched on

Preset time delay
(0.1 - 1s)

Dust dispersion system activate

Event signal sent to recorder

Preset ignition delay $t'_v$ (0.01 - 2s)

Ignition source activated

Event signal sent to recorder

Preset time delay
(0.1 - 2s)

Dust dispersion system isolated

U.V. recorder chart drive switched off

Ignition circuit isolated
(capacitor discharged)

END
Since it was essential to operate the explosion event remotely, the control unit also activated the high energy discharge capacitor charging circuit.

Safety was a major consideration throughout the design and construction of all explosion test apparatus; the design philosophy being to prevent incorrect operation and foreseeable mistakes that could result from forgetfulness. The following safety features were incorporated into the design of the control unit and capacitor discharge unit:

(i) key switch - the single key must be carried by the operator when he is working on/in the explosion test vessel;

(ii) sonic alarm - two buzzers, one on the control unit and one on the capacitor unit provide audible alarms whilst the system is enabled;

(iii) plugs and leads - connectors were chosen such that it was impossible to incorrectly 'plug up' the apparatus and safety interlocks ensured that the system could not be 'enabled' until all interconnecting leads were plugged in;

(iv) mains trip - in the event of mains failure the ignition circuit was isolated and the capacitor discharged;
a trip wire was installed at the entry to both the concrete block house for 43 dm³ tests and the test site used for 6.2 m³ tests. Neither danger zones could be approached without automatically inhibiting the ignition circuits and discharging the capacitor.

The control unit is shown in Plate VIII.

4.1.4. Mensuration

Kistler piezo-resistive transducers (Type 2045.20A) coupled to Kistler bridge amplifiers (Type 4601) were used to monitor the explosion pressure in all test apparatus, except the 1m³ vessel, which was instrumented with Kistler piezoelectric transducers. The output from each bridge amplifier was fed to Southern Instrument galvanometer amplifiers (Type 40502), which drove SMIJ type galvanometers fitted in a Southern Instrument series 4500 U.V. Oscillograph recorder. The frequency response of the recording system was limited by the natural frequency of the chosen galvanometer torsion wire; for SMIJ type galvanometers this is ~3.3 kHz. The U.V. recorder had a maximum chart speed of 5m s⁻¹ and an internal timebase which could superimpose timing lines on the record at 2, 10 or 100ms intervals. Two galvanometer
drive amplifiers were connected to each transducer in order to provide both a high sensitivity (1mm = 0.002 MPa) and a low sensitivity (1mm = 0.01 MPa) record of the pressure at each measuring location. Experiments in the 1m³ and 6.2m³ vessels used two transducers, whereas tests in the smaller vessels relied on a single transducer.

The Kistler bridge amplifiers were calibrated to provide an output of 0.5V MPa⁻¹ and each galvanometer amplifier was calibrated to provide the required mm V⁻¹ deflection. The calibration of each pressure measuring system was checked at the beginning of each day's work using a comparator hydraulic pump and a standard pressure test gauge, or using a 'dead weight' tester. The pressure transducer output(s) were also optionally recorded onto magnetic tape using a Philips EL1020FM data recorder. Calibration of this record was provided by discrete voltage stops.

Figure 9 shows a schematic diagram of the experimental layout and a typical explosion record is shown in Figure 10. The following data were obtained from the experimental trace, as appropriate:

\[
\begin{align*}
  t_v' & \quad - \text{preset ignition delay} \\
  t_v & \quad - \text{actual ignition delay} \\
  E & \quad - \text{capacitor discharge voltage} \\
  P_0 & \quad - \text{initial pressure (gauge)} \\
  P_{\text{max}} & \quad - \text{maximum explosion pressure (gauge)} \\
  \left(\frac{dP}{dt}\right)_{\text{max}} & \quad - \text{maximum rate of pressure rise}
\end{align*}
\]
The event signals provided by the control electronics define the preset ignition delay $t^'$. Note that the actual ignition delay $t_v$ may be greater than the preset value with ignition using a train of induction coil sparks.

### 4.1.5. Test Procedures

The experimental procedures were essentially the same in the five explosion test apparatus. Note that some of the test procedures used differ from the 'standard' test methodology described above for the $1m^3$ and Hartmann apparatus.

#### 4.1.5.1. Quiescent Gas Explosions

a) **Hartmann Apparatus, 1:1 Aspect Ratio Vertical Tube, and 43 dm$^3$ Spherical Apparatus.**

Dalton's law of partial pressures was used to calculate the concentration of fuel gas prepared. The following procedure was found to reproducibly prepare the required gas/air concentration:

(i) the explosion vessel was flushed with compressed air. A cylinder of 21% oxygen in nitrogen was used as air substitute in these experiments;

(ii) fuel gas was released into the explosion vessel until a predetermined pressure was attained;

(iii) the explosion vessel was pressurised rapidly to 0.15 MPa with compressed air. Injection was usually through a spray pipe to improve mixing. The resultant overpressure was released slowly, and a sample of the prepared gas mixture collected in an IR absorption spectrophotometer gas cell;
(v) the vessel outlet valve was shut, the gas cell taps were shut and the explosion initiated using induction coil or capacitive discharge spark;

(vi) the gas concentration was measured by the IR absorbance of the CH\textsubscript{4} peak at 6.6 - 7.1\textmu m wavelength (CH\textsubscript{2} scissor) using a Pye Unicam SP2000 IR spectrophotometer. The volume % of CH\textsubscript{4} was determined from a calibration of IR absorbance using known gas/air samples. This procedure was accurate to within ± 1/2 volume %;

(vii) the gas concentration was calculated using Daltons law of partial pressures. In general, agreement between measured and calculated concentration levels was better than 1 volume %.

b) Bartknecht 1m\textsuperscript{3} Vessel

The required gas concentration was prepared by the method of partial pressures using a similar procedure to that described in (a) above. The prepared gas/air mixture was sampled and analysed using IR absorption spectroscopy. The overpressure was released, the vessel valves closed, and the combustible mixture ignited by an induction coil spark across a 4mm spark gap.

c) The 6.2 m\textsuperscript{3} IEP Test Facility

The following experimental procedure was found to give reproducible quiescent gas explosibility results in this test apparatus (see also section 4.5.7).
(i) the vessel was purged with compressed air;

(ii) a 45 dm$^3$ fuel gas reservoir was charged with the fuel gas to a predetermined pressure;

(iii) this combustible gas was rapidly released through a spray pipe into the explosion chamber;

(iv) a 200mm diameter safety fan was used to stir the gas/air mixture for 10 minutes;

(v) the fan was switched off and the overpressure released;

(vi) the explosion was initiated by a spark across central electrodes;

(vii) the gas concentration was estimated* by calculation using Daltons law of partial pressures.

4.1.5.2. Turbulent Gas Explosions

Turbulent gas explosions were undertaken using experimental procedures which were similar to those used to produce dust explosions in the various test apparatus. The explosion chambers were filled with the required concentration of combustible mixture, and compressed premixed gas/air was injected into the chamber to induce turbulence.

* It was impractical to measure the prepared gas concentrations in these tests because the test apparatus was sited some 80 miles from available laboratory facilities.
The small 'air reservoir' was charged with a defined concentration of fuel gas/air to 0.82 MPa. The explosion tube was charged with the same fuel gas/air mixture at atmospheric pressure. The compressed combustible charge was released into the explosion chamber, thus producing a turbulent fuel gas/air mixture which was ignited after a predetermined ignition delay using a discrete ignition source.

43 dm$^3$ Spherical Apparatus, Bartknecht 1m$^3$ Vessel

The 'dust dispersion canister' was charged with a defined concentration of fuel gas/air by the method of partial pressures to a pressure commensurate with the air pressure used to disperse dust in the test apparatus. The explosion chamber was charged with the same fuel gas/air mixture at atmospheric pressure. The compressed combustible charge was released into the explosion chamber through the spray ring disperser, thus creating a turbulent gas/air mixture. The explosion was initiated after a predetermined ignition delay using a discrete spark ignition source.

4.1.5.3. Dust Explosions

The following experimental sequences were used with these test apparatus:

(i) dust sample was dispersed onto a hot coil ignition source
- STANDARD METHODOLOGY;

(ii) dust sample was dispersed onto a train of induction coil sparks as an ignition source - STANDARD METHODOLOGY;
(iii) dust sample was dispersed into the explosion tube and a train of induction coil sparks was initiated after a preset ignition delay $t'_{v}$;

(iv) dust sample was dispersed into the explosion tube and the explosion initiated, after a preset ignition delay, with a fuse head igniter;

(v) dust sample was dispersed into the explosion tube and the explosion initiated, after a preset ignition delay, with a 100J capacitive spark.

b) **43 dm$^3$ Spherical Apparatus**

A weighed dust sample was loaded into the dust dispersion canister, which was subsequently pressurised with compressed air. The following experimental sequences were used with this apparatus:

(i) dust sample was dispersed, via pepper pot spreader, onto a train of induction coil sparks as an ignition source;

(ii) dust sample was dispersed, via a pepper pot spreader, and a train of induction coil sparks was initiated after a preset ignition delay $t'_{v}$;

(iii) dust sample was dispersed, via a pepper pot spreader, and the explosion was initiated after a preset ignition delay by a capacitive discharge ignition source;

(iv) dust sample was dispersed, via a spray ring, and the explosion was initiated after a preset ignition delay by a capacitive discharge ignition source.
c) **Bartknecht 1m³ Vessel**

All of the reported dust explosibility test results in this apparatus were obtained using the standard test procedure described in 4.1.1.1. above.

d) **6.2 m³ IEP Test Facility**

Weighed dust samples were loaded into three dust dispersion canisters which were subsequently pressurised to 2 MPa with compressed air. The dust was dispersed into the explosion chamber through three semi-circular spray rings, and the dust cloud was ignited by a 100J capacitive spark after a preset ignition delay. Full details of the test apparatus and test procedures are given in section 4.5.

### 4.1.6. Selection of Test Explosible Fuels

The following fuels were chosen by the ISO Committee for explosion suppression experiments.

1) 

2) 

3) Coal Dust

4) Cellulose Dust

### 4.1.6.1. Gases

Experimental work on combustible gases was restricted to CH₄, 70/30 CH₄/H₂ and C₃H₈. The gases were supplied by British Oxygen Company as:

- Methane CP - Commercial product grade
- 70/30 CH₄/H₂* - prepared to order - assay certified
- Propane CP - Commercial product grade

* 70/30 CH₄/H₂ was claimed by ISO delegates to represent the same explosion hazard as C₃H₈.
4.1.6.2. Dusts

Experimental work was undertaken on a range of industrial dusts. However, cellulose dust was chosen as the main test dust. Its explosibility is similar to that of many dusts commonly encountered in industry. A large batch of cellulose dust, type BOOX, was supplied by:

J. Rettenmainer & Söhne,
Fullstoffwerke,
7091, Holzmühle,
W. Germany.

This batch (WM) was compared with the batch (BVS) of cellulose dust from the same supplier used in the 1m$^3$ test work in Dortmund.

Tests in the Hartmann apparatus, using hot coil ignition, identified the most explosible concentration of the WM batch as 0.8kg m$^{-3}$ . This concentration was used in comparative tests between BVS and WM cellulose batches.

Results of tests in the standard Hartmann apparatus are shown in Table 4.1.

<table>
<thead>
<tr>
<th>CELLULOSE BATCHE</th>
<th>IGNITION SOURCE</th>
<th>n</th>
<th>$P_{max}$</th>
<th>$(\frac{dP}{dt})_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>MPa</td>
<td>MPa s$^{-1}$</td>
</tr>
<tr>
<td>BVS</td>
<td>Induction coil sparks</td>
<td>10</td>
<td>0.81</td>
<td>25.3</td>
</tr>
<tr>
<td>WM</td>
<td></td>
<td>10</td>
<td>0.83</td>
<td>26.4</td>
</tr>
<tr>
<td>BVS</td>
<td>Hot coil</td>
<td>25</td>
<td>0.77</td>
<td>34.2</td>
</tr>
<tr>
<td>WM</td>
<td></td>
<td>25</td>
<td>0.74</td>
<td>33.4</td>
</tr>
</tbody>
</table>

TABLE 4.1.

where $n$ is the number of experimental measurements.
These test results demonstrated that the BVS and WM batches of cellulose dust type BOOX were not significantly different in terms of their explosible characteristics. The observed difference between hot coil and induction spark ignition is typical of that found for most industrial dusts. A sample of the WM batch was dried in an oven for 4 hours at 110°C, and subsequently characterised in the standard Hartmann apparatus see Table 4.2.

<table>
<thead>
<tr>
<th>CELLULOSE BATCH</th>
<th>IGNITION SOURCE</th>
<th>n</th>
<th>$P_{\text{max}}$</th>
<th>$(\text{d}P/\text{d}t)_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WM - Dried</td>
<td>Induction coil sparks</td>
<td>5</td>
<td>0.79</td>
<td>40.2</td>
</tr>
<tr>
<td>WM - Dried</td>
<td>Hot coil</td>
<td>5</td>
<td>0.72</td>
<td>45.7</td>
</tr>
</tbody>
</table>

**TABLE 4.2.**

The explosion violence of the dried sample was ~30% greater than the 'as received' cellulose dust. Both the BVS and WM batches had a nominal moisture content of 8 weight % in the 'as received' condition. Since moisture content has such an influence on the explosible characteristics of cellulose dust, it was necessary to monitor this parameter throughout the programme of experiments to ensure that it remained essentially invariant. Cellulose dust explosion tests reported in this thesis were all undertaken using cellulose, type BOOX, with a nominal moisture content of 8 weight %. A scanning electron micrograph, Plate IX, shows the fibrous nature of the cellulose particulates. A particle size analysis of the WM batch identified the median particle dimension as 56 x 22μm.
PLATE IX: Cellulose Dust Particle Size Analysis
4.2. Explosion Suppressants

A small test programme was carried out to compare the inhibiting effectiveness of vapour phase Halon suppressants, inerting gases and powder suppressants. The influence of each of these agents on the explosion violence of cellulose dust was determined in the standard Hartmann vertical tube apparatus. In all tests, ignition was by a single induction coil spark at $t_v = 100\text{ms}$.

To eliminate any systematic error a 'TEST vs CONTROL' experimental procedure was used. A minimum of five measurements at each concentration of each suppressant were completed. After each group of five 'TEST' experiments, the test apparatus was purged of any residual agent and five 'CONTROL' experiments were undertaken — in which the cellulose dust sample was ignited in the absence of any suppressant agent. The percentage deviation between the 'TEST' and the corresponding 'CONTROL' explosibility parameters provides data on the influence of the agent on the explosion characteristics of cellulose dust.

4.2.1. Halons

The Halon vapour was added to the air inside the explosion tube using a calibrated syringe. After the cellulose dust sample had been loaded into the apparatus the syringe needle was inserted through a rubber septum and an open valve, into the centre of the explosion tube. The Halon was injected into the air, the syringe needle withdrawn and the valve closed. The explosion test was completed using a discrete induction spark ignition procedure. Tests were carried out with Halon 1211 and Halon 1301 vapours.

4.2.2. Inert Gases

The cellulose dust sample was loaded into the test apparatus, and the apparatus sealed tight. A predetermined pressure of inerting gas was released into the explosion tube. The pressure was measured with a water
manometer. The overpressure inside the explosion tube was released, the valves closed and the explosion test undertaken. The two inerting gases studied were carbon dioxide and nitrogen.

4.2.3. Powders

A weighed sample of agent was thoroughly mixed with the cellulose dust sample in the bottom cup of the Hartmann apparatus. The apparatus was assembled, and the explosion test undertaken. The two powders studied were china clay (essentially an inert powder) and a monoammonium phosphate based suppressant.

4.3. Explosion Suppressors

4.3.1. Experimental Arrangement

The discharge characteristics of hemispherical and HRD suppressors were measured on an open test range. The experimental arrangements used for these measurements are shown in Figure 11. The spatial and temporal discharge profiles were filmed with 'Fastax' and 'Hyspeed' cameras at 2000 pps. A Bolex camera was used to provide a colour record of the discharge (64 pps). HRD suppressors were instrumented so as to measure their depressurisation and mass discharge characteristics.

4.3.2. Preparation of HRD Suppressors

The frangible diaphragm of the 76 mm outlet diameter HRD suppressor used for liquid suppressant was pre-stressed and the canister and diaphragm hydraulically tested before final assembly. To ensure complete safety HRD suppressors were not pressurised with nitrogen until they had been mounted in their final firing position. The detonator was fitted and connected to the firing circuit, which was then enabled using a key switch.
4.3.3. Mensuration

When a HRD suppressor is discharged the force acting on the spreader head is a measure of the momentum exchanged as the suppressant is dispersed by the spreader. Measurement of this thrust provides an estimate of the mass discharge rate of suppressant. Strain gauge networks were mounted on the spreader surface to measure this force - although meaningful calibration was confounded by the spreader geometry. Canister depressurisation was monitored using a piezo-resistive pressure transducer fitted to the canister wall.

The 'Fastax' high speed camera had a slower film acceleration than the 'Hyspeed' camera. Hence it was necessary to provision a delay circuit between the two cameras to ensure that both were running at their selected film speeds when the discharge was initiated. A 1kHz oscillator driving LEDs provided timing marks on the films' edges. An 'event initiate' switch was triggered by the 'Hyspeed' camera after a preset film footage, and activated the detonator firing circuit, and event signals to LEDs which provided an 'event initiate' reference on the other edges of the two films. Hence, the exact film speed, and the precise point in time that the suppressor was fired could be determined from the high speed film records.

The depressurisation and mass discharge characteristics of the HRD suppressors were recorded using a U.V. oscillograph record. An 'event initiate' signal was also provided to this recording system.
4.4. Explosion Suppression

4.4.1. Collaborative Trials Using The Bartknecht 1m$^3$ Vessel

Section 4.1. describes the experimental procedure used to produce and monitor unsuppressed gas and dust explosions in the 1m$^3$ vessel. The suppression system evaluated in the collaborative trials was based on a single 76mm outlet diameter HRD suppressor. The suppressor canister had a free volume of 5.4 dm$^3$, and was filled with a measured quantity of suppressant. The HRD suppressor was mounted centrally on the top of the 1m$^3$ vessel, and was pressurised with nitrogen gas. A 'pepper pot' hemispherical spreader was used to disperse the contents into the test volume.

An electronic discriminator was set to activate the suppressors when a predetermined threshold voltage was recorded at the output of a pressure transducer. The pressure transducers were re-calibrated each day, and unsuppressed explosion tests were periodically undertaken to ensure that fully developed explosions were being achieved in the test vessel. Between each experiment the test chamber was hosed down with water and allowed to cool to ambient temperature.

4.4.2. Explosion Suppression Trials Using The IEP Test Facility

The 6.2 m$^3$ IEP test facility was set up and instrumented as part of this study. Details of the test apparatus and of the experimental test procedures are described fully in section 4.5. below.

A range of explosion suppression trials were undertaken against both quiescent gas and turbulent dust explosions in the 6.2 m$^3$ test facility. The explosion suppression hardware used in these trials included 5 dm$^3$ hemispherical suppressors and 76mm outlet diameter HRD suppressors with
suppressant capacities of 3 dm$^3$, 4 dm$^3$, 10 dm$^3$ and 30 dm$^3$. All HRD suppressors were fitted with 'pepper pot' spreaders to effectively disperse the suppressant into the explosion chamber. The five alternative locations for explosion suppressors on the 6.2 m$^3$ test vessel are identified as A - E in Figure 12. The combinations of explosion suppressors used in these trials are summarised in Table 4.3 below.

<table>
<thead>
<tr>
<th>No. of Suppressors</th>
<th>Type of Suppressor</th>
<th>Suppressant Capacity (dm$^3$)</th>
<th>Suppressor Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Hemispherical</td>
<td>5</td>
<td>A, C</td>
</tr>
<tr>
<td>3</td>
<td>HRD</td>
<td>3</td>
<td>A, B, C</td>
</tr>
<tr>
<td>4</td>
<td>HRD</td>
<td>3</td>
<td>A, B, C, D</td>
</tr>
<tr>
<td>3</td>
<td>HRD</td>
<td>4</td>
<td>A, B, C</td>
</tr>
<tr>
<td>1</td>
<td>HRD</td>
<td>10</td>
<td>D</td>
</tr>
<tr>
<td>3</td>
<td>HRD</td>
<td>10</td>
<td>A, B, C</td>
</tr>
<tr>
<td>1</td>
<td>HRD</td>
<td>30</td>
<td>D</td>
</tr>
<tr>
<td>4</td>
<td>2 Hemispheres</td>
<td>5</td>
<td>A, C</td>
</tr>
<tr>
<td></td>
<td>2 HRDs</td>
<td>3</td>
<td>B, D</td>
</tr>
</tbody>
</table>

**TABLE 4.3.**

Note that HRD suppressors fitted to position D or E are fitted with 90° elbows.

The pressure transducers were calibrated before each explosion suppression trial. The explosion chamber was thoroughly cleaned and hosed down with water after each experiment. In practice, it was not possible to undertake more than one test on any day.

* the apparent density of monoammonium phosphate powder was $\sim 1$ kg dm$^{-3}$, hence a suppressant charge of 4kg corresponds to a suppressant capacity of 4 dm$^3$. 
4.5. The IEP Test Facility

A major objective of this study was to set up a large volume explosion test facility in the UK in accordance with the recommendations of ISO/TC21/SC5/WG3. Such a test vessel must be capable of containing unsuppressed gas and dust explosions, and must be sited and operated in accordance with the mandatory requirements for such work.

4.5.1. The Chosen Strategy

Graviner Ltd. offered some finance for this venture, and sought collaborative funding of a UK test facility. However, there was insufficient interest in such a venture and the ideal option of establishing a purpose built stainless steel large volume explosion test vessel was out of the question. It was therefore chosen to seek to set up a 'Graviner' IEP (Industrial Explosion Protection) test facility with the limited financial resource available.

After an extensive search, a second hand mild steel pressure vessel was located at a disused gas manufacturing plant. This vessel was a 6.2 m³ LPG vaporiser which had a certified working pressure of 2 MPa and a hydraulic test pressure of 3 MPa. The intention of modifying this pressure vessel to an explosion test chamber was discussed with pressure vessel experts, and it was chosen to risk the necessary investment and seek to use this pressure vessel as the basis of the IEP test facility.

Since explosion research on this scale must be insured and licensed such a test facility must be suitably located. The only appropriate Wilkinson Match site for such test work was Pains-Wessex pyrotechnic manufacturing and testing centre at High Post, Salisbury. The storage and handling of explosives was approved on this site, and 24 hour security was assured.
4.5.2. Modifications to LPG Vaporiser

Plate X shows the 6.2 m³ pressure vessel as purchased from British Gas. After purchase, the pressure vessel was hydraulically tested and examined. No signs of distress were noted. The following modifications were, therefore, progressed by sub-contractors:

(i) flame cut a 0.6 m diameter hole in one of the dished ends of the vessel to permit entry;

(ii) cut out and remove all internal steam pipes;

(iii) machine and weld into place a 0.45 m internal diameter annulus to form a manhole entry point at one end of the vessel;

(iv) machine and fit a steel door to this manhole;

(v) machine three 0.11 m internal diameter annuli; and three 0.03 m internal diameter annuli;

(vi) cut out holes and weld the six annuli into place to form additional ports in the vessel wall;

(vii) stress relieve all welds by heat treatment in a large furnace;

(viii) hydraulically pressure test the modified pressure vessel to 3 MPa.
PLATE X: Disused LPG Vaporiser
These modifications provided the pressure vessel with alternative locations for explosion suppression hardware, and with sufficient other ports to facilitate fuel injection, air purge, drainage and fitting of measuring devices; see Figure 12.

4.5.3. Site Preparations

The 6.2 m³ pressure vessel was installed on a 4m x 4m concrete pad in a 3 m deep pit which was adjacent to an earth mounded building. The pit was surrounded by 2 m high earth mounds. Concrete steps provided access onto the explosion test site. A steel 'cat walk' was fabricated around two sides of the explosion test vessel and an open shelter was constructed over the test site to provide a measure of weather protection. An RSJ was fitted longitudinally 2 m above the pressure vessel as part of the shelter structure. Lifting tackle was fitted to this RSJ to assist in the installation of the larger HRD suppressors on the test vessel. A soak-away was prepared in one corner of the test site and water, electricity and compressed air supplies installed. Since a large quantity of air was essential to purge the vessel after an explosion test a 1.2 m³ air reservoir was installed on the test site.

All control and measuring equipment was set up in the earth mounded building. All cable runs between this building and the test site were permanently installed in armoured sheaths. Weather proof terminal boxes were fitted to these cable runs and were mounted under the weather shelter.
4.5.4. The IEP Test Facility

Plate XI shows the IEP test facility set up at High Post, Salisbury. It was designed to facilitate gas, flammable liquid and dust explosion and explosion suppression research. A diagram of the final installation is shown in Figure 12.

Gas injection was achieved through a single 12mm diameter valve. A 45 dm$^3$ reservoir was charged with the fuel gas, and this charge released, via the manual valve, into the vessel. A long spray pipe inside the vessel helped to improve mixing of the combustible gas. Provision was made for a circulating fan to be fitted inside the pressure vessel to ensure complete mixing of the combustible gas. The early stages of gas explosion tests could be filmed through a sight glass, which could be optionally fitted to any one of the 0.11 m diameter ports.

Dust dispersion was achieved using three identical systems, each consisting of a 5.4 dm$^3$ dust reservoir, a fast acting valve and a perforated semi-circular spray ring. The fast acting ball valve was pneumatically operated and specifically developed for this purpose. High speed film records have shown that the pneumatically operated valve opens in $\sim 80\text{ms}$, and that the subsequent dispersion time of $1\frac{1}{2}$ kg of dust was $\sim 780\text{ms}$. The spray rings were constructed of 19mm diameter steel tube, which was formed and drilled with an array of nineteen 4mm diameter holes. They were detachable for cleaning.

A remotely operated 'exhaust' valve was fitted to the vessel. After an experiment this valve would be opened to purge the vessel of noxious gases. The combustion products were passed through a crude water scrubber.
PLATE XI: 6.2m$^3$ IEP Test Facility
before being released into the environment. For final air purge after a
test a venturi 'air mover' was used. This provided a large airflow through
the explosion chamber. Complete depressurisation of the air reservoir via
the venturi was equivalent to four air changes in the explosion chamber.

A multiprobe flame proximity detector was designed to enable the course
of flame propagation to be monitored inside the 6.2 m$^3$ vessel, see Plate
XII. Each measuring location consisted of a simple ionization probe set
up to monitor the increased air conductivity as the flame front sweeps the
probe gap. This device was specifically developed to study the flame speed
characteristics of quiescent gas/air explosions in the 6.2 m$^3$ vessel.

4.5.5. **Licensing, Insurance and Safety**

A red flag was displayed outside the mounded building to warn other work­
ers on the Pains Wesséx site that experimental work involving explosions
and/or explosives was in progress; a flashing beacon was placed across
the path between the mounded building and the test site. An audible alarm
was sounded immediately prior to an explosion or explosion suppression
test.

The pressure vessel was insured for the purpose of explosion and explosion
suppression research against all third party liability. It was periodically
inspected and hydraulically tested. The insurers required that the press­
ure vessel was fitted with a 75mm diameter rupture disc for all un-
suppressed explosion tests. This disc was rated to rupture at an over­
pressure of 1.2 MPa.
PLATE XII:
Multiprobe Flame Proximity Detector
Annexes licensed by HMIE to store class six division two and class six division three explosives were installed adjacent to the mounded building. This building, and the test site, were licensed for the assembly of appropriate explosive devices and the author was certified to handle and transport such explosives in accordance with Home Office regulations.

Entry of the pressure vessel was only allowed in accordance with the HSE regulations for the entry of confined spaces. In particular:

(i) the atmospheric conditions shall not be flammable;

(ii) the atmospheric conditions shall not be toxic;

(iii) ventilation shall be provided corresponding to a minimum of five air changes per hour;

(iv) entry shall be supervised by an able bodied person who shall monitor the progress of the person inside the vessel.

A minimum of two personnel were required for all explosion test work. Such personnel were required to wear protective clothing (e.g. boiler suits, rubber boots and safety helmets). Draeger gas detection kits were available for CH\textsubscript{4}, HCl, HBr, Br\textsubscript{2}, Cl\textsubscript{2} and CO gases, and a LEL meter was provided for flammable gas detection. Through-flow canister gas masks were always available to protect against toxic concentrations of combustion products, Halon pyrolysis products, and/or dusts.

An operational safety manual was prepared and used for all test work on this site.
4.5.6. **Test Facility Instrumentation**

Details of the control and sequencing unit used with the 6.2 m³ test facility are described in section 4.1.3. Modifications to it were made to permit the necessary synchronisation for the remote operation of a high speed cine camera, which was occasionally used to film the explosion in the vessel. The control and sequencing unit was interfaced with a discriminator and suppressor firing circuit for explosion suppression tests.

The discriminator was used to simulate an explosion pressure detector. When the output from the central pressure transducer attained a predetermined voltage (corresponding to a detection pressure, \( P_A \)) a thyristor triggered the suppressor firing circuit. Since the experimental procedure used to disperse dust into the test apparatus resulted in an overpressure, \( P_o \), at ignition, it was necessary for the discriminator to superimpose the predetermined detection pressure, \( P_A \), on the overpressure \( P_o \) to provide the correct detection pressure for the test. The discriminator also provided an event signal corresponding to 'detection' for recorders. A 'test' switch enables the discriminator to be set to operate at the required voltage (pressure threshold) without charging the suppressor firing circuit.

The suppressor firing circuit was thyristor triggered, and proved particularly troublesome during commissioning. It was found that the thyristor was momentarily switched on by 'pick up' when the high energy capacitive spark ignition circuit was activated. Hence the suppressors were 'fired' coincident with ignition of the explosion. This fault could not be eliminated by screening, or capacitive filtering. The final solution to the problem was to use a relay to isolate the detonator circuit from the suppressor firing circuit. This relay was energised coincident with ignition of the explosion.
The finite operating time of the relay (≈10ms) ensured that the suppressors would not be activated by extraneous 'pick up' because they were isolated until after the ignition source had been operated.

Safety was a major consideration in the design of the suppressor firing system. The following safety features were incorporated into the design:

(i) the discriminator and suppressor firing circuits were fully interlocked with the control system;

(ii) the key switch and 'enable' switch provided on the control unit also 'armed' the suppressor firing circuit;

(iii) a small bleed current was used to monitor the detonator circuit. All detonators were series wired. If an open circuit, or earth fault condition, occurred the complete system would not 'enable';

(iv) remotely operated valves were interlocked such that the system could not be 'enabled' if any one valve was open;

(v) the suppressor firing circuit was automatically isolated, and the capacitor used to provide the firing current discharged within 2s of each test.

4.5.7 Test Procedures

The experimental procedures used for gas and dust explosion and explosion suppression trials in the 6.2 m³ test vessel are summarised briefly below.
4.5.7.1. Unsuppressed Quiescent Gas Explosions

1. Ensure that the red flag and flashing beacon are displayed.

2. Purge explosion chamber with compressed air.

3. Check integrity of control electronics, ignition circuit and measuring equipment.

4. Close and seal explosion chamber.

5. Check that all inlet and outlet valves are closed.

6. Fill the 45 dm$^3$ fuel gas reservoir with the required pressure of flammable gas.

7. Release this gas charge into the explosion chamber and close gas inlet valve.

8. Vacate test site and attach 'trip wire' across entrance.

9. Allow gas to mix for 15 minutes (or use circulating fan to mix gas).*


11. Ensure that all personnel are in mound building.

* Most tests were undertaken using the circulating fan to ensure complete mixing, however it was proven that tests without using the circulating fan gave identical explosion results.
12. Enable systems and sound alarm.


14. Switch off all circuits.

15. Open remotely operated exhaust valve and purge combustion products through water scrubber.

16. Ensure that there is no residual pressure in vessel.

17. Open vessel door and remove top plate A.

18. Insert venturi air mover in port A and purge vessel.

4.5.7.2. Unsuppressed Dust Explosions

1. Ensure that red flag and flashing beacon are displayed.

2. Purge explosion chamber with compressed air.

3. Check integrity of control electronics, ignition circuit and measuring equipment.

4. Ensure that dust dispersion pneumatic valves are closed.

5. Charge dust dispersion systems with measured quantities of the fuel dust.
6. Close and seal explosion chamber.

7. Check that all inlet and outlet valves are closed.

8. Pressurise dust dispersion canisters with compressed air to 2 MPa.

9. Pressurise dust dispersion pneumatics to 1.6 MPa.

10. Vacate test site and attach 'trip wire' across entrance.

11. Ensure that all personnel are in mounded building.

12. Enable systems and sound alarm.


14. Switch off all circuits.

15. Open remotely operated exhaust valve and purge combustion products through water scrubber.

16. Ensure that there is no residual pressure in vessel.

17. Open vessel door and remove top plate A.

18. Insert venturi air mover in port A and purge vessel.

19. Hose down vessel with water.

20. Clean out dust dispersion systems.
4.5.7.3. Explosion Suppression Trials

1. Mount explosion suppressors (unpressurised) on/in the test vessel as appropriate.

2. Check the integrity of the discriminator and suppressor firing circuits.

3. For gas trials undertake 4.5.7.1. instructions 1 - 5. For dust trials undertake 4.5.7.2. instructions 1 - 7.

4. Pressurise explosion suppressors with nitrogen as appropriate.

5. Fit explosive detonators as appropriate.

6. Connect up suppressor firing circuit and check integrity of wiring.

7. For gas trials undertake 4.5.7.1. instructions 6 - 18. For dust trials undertake 4.5.7.2. instructions 8 - 20.

Note that a large quantity of noxious gases can be produced if a 'Poor' suppression or 'Failed' suppression results. Personnel must wear protective masks and these gases must be slowly purged through the water scrubber before the vessel can be opened.
5. RESULTS

5.1. Explosions

The results of unsuppressed gas and dust explosion experiments in the five test apparatus described in section 4.1. are presented below. Details of the measurements taken from pressure/time records of the explosion events are identified in Figure 10 (see section 4.1.4.). The burning velocities, $S_u$, were calculated from the early part of the pressure/time records, as described in section 3.1.1. The turbulence parameters $\lambda$ and $T_u$ were calculated using equations defined in section 3.1.2.

5.1.1. The Bartknecht 1m$^3$ Vessel

5.1.1.1. Gas Explosion Tests

Explosibility measurements of quiescent CH$_4$ and 70/30 CH$_4$/H$_2$ combustible gases, mixed with air, are presented graphically in Figures 13 and 14. Table 5.1. summarises the measured explosibility parameters of the most explosible concentrations of these combustible gases.

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION</th>
<th>$P_{\text{max}}$</th>
<th>$(dP/dt)_{\text{max}}$</th>
<th>$S_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>9%</td>
<td>0.74</td>
<td>5.8</td>
<td>0.31</td>
</tr>
<tr>
<td>70/30 CH$_4$/H$_2$</td>
<td>15%</td>
<td>0.72</td>
<td>10.3</td>
<td>0.52</td>
</tr>
</tbody>
</table>

**TABLE 5.1**

The effect of induced turbulence on the explosion parameters of the most explosible flammable gas concentrations was studied. These results are presented in Table 5.2.
<table>
<thead>
<tr>
<th>GAS</th>
<th>( t_v ) s</th>
<th>( P_0 ) kPa</th>
<th>( P_{\text{max}} ) MPa</th>
<th>( \frac{\text{d}P}{\text{d}t}_{\text{max}} ) MPa s(^{-1} )</th>
<th>( \alpha S_u ) m s(^{-1} )</th>
<th>( \zeta )</th>
<th>( \zeta )</th>
<th>( \zeta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 Vol % CH(_4)</td>
<td>0.3</td>
<td>10</td>
<td>0.85</td>
<td>54.9</td>
<td>2.55</td>
<td>7.7</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>14</td>
<td>0.88</td>
<td>28.2</td>
<td>1.33</td>
<td>4.0</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>14</td>
<td>0.90</td>
<td>25.0</td>
<td>0.93</td>
<td>2.8</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>10</td>
<td>0.90</td>
<td>15.5</td>
<td>0.72</td>
<td>2.2</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>15 Vol %</td>
<td>0.3</td>
<td>12</td>
<td>0.88</td>
<td>76.0</td>
<td>3.79</td>
<td>7.3</td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>15</td>
<td>0.88</td>
<td>41.9</td>
<td>1.88</td>
<td>3.6</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>14</td>
<td>0.86</td>
<td>28.7</td>
<td>1.10</td>
<td>2.1</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>70/30 CH(_4)/H(_2)</td>
<td>1.5</td>
<td>20</td>
<td>0.87</td>
<td>19.1</td>
<td>0.98</td>
<td>1.9</td>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 5.2.**

5.1.1.2. Dust Explosion Tests

Explosibility data of cellulose dust and bituminous coal dust dispersions in the 3 m\(^3\) vessel, measured using the standard test procedure \( t_v = 0.6 \) s, are presented graphically in Figures 15 and 16. Table 5.3 summarises the measured explosibility parameters of the most explosible concentrations of the two combustible dusts.

<table>
<thead>
<tr>
<th>DUST</th>
<th>CONCENTRATION kg m(^{-3})</th>
<th>( P_{\text{max}} ) MPa</th>
<th>( \frac{\text{d}P}{\text{d}t}_{\text{max}} ) MPa s(^{-1} )</th>
<th>( S_u ) m s(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>0.75</td>
<td>0.92</td>
<td>15.5</td>
<td>0.78</td>
</tr>
<tr>
<td>Coal</td>
<td>0.25</td>
<td>0.84</td>
<td>7.5</td>
<td>0.36</td>
</tr>
</tbody>
</table>

**TABLE 5.3**
This standard dust explosion test methodology resulted in a large variation in \( \frac{dP}{dt} \) values at the most explosible dust concentrations. Cellulose dust \( \frac{dP}{dt} \) measurements varied from 8.6 to 16.3 MPa s\(^{-1}\), the average of seven measurements being 12.8 MPa s\(^{-1}\). The average calculated burning velocity data for cellulose and coal dust explosions were 0.59 m s\(^{-1}\) and 0.29 m s\(^{-1}\) respectively.

5.1.2. The Hartmann Vertical Tube Apparatus

Gas and dust explosion experiments were undertaken in this apparatus using the standard test procedures. Additional experiments were carried out using increased ignition delays, and using discrete ignition procedures.

5.1.2.1. Gas Explosion Tests

Explosibility measurements of quiescent \( \text{CH}_4 \)– air mixtures are presented in Figure 17. Table 5.4. summarises the explosion parameters of the most explosible concentration of this fuel.

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION</th>
<th>( P_{\text{max}} ) MPa</th>
<th>( \frac{dP}{dt} )(_{\text{max}} ) MPa s(^{-1})</th>
<th>( S_u ) m s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{CH}_4 )</td>
<td>9.5 Vol %</td>
<td>0.60</td>
<td>27.5</td>
<td>0.33</td>
</tr>
</tbody>
</table>

TABLE 5.4.

A typical pressure/time record for the explosion of a quiescent combustible gas in the Hartmann apparatus is shown in Figure 18. It is evident that a fully developed quiescent gas explosion is not attained in this apparatus, and that the maximum rate of pressure rise occurs early in the explosion pressure development.
The effect of induced turbulence on the explosion parameters of 9.5 Vol % CH₄ - air explosions in the Hartmann apparatus is demonstrated by the results summarised in Table 5.5.

<table>
<thead>
<tr>
<th>GAS</th>
<th>tᵥ</th>
<th>P₀</th>
<th>P_max</th>
<th>(dP/dt)ₘₐₓ</th>
<th>Tu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ms</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa s⁻¹</td>
<td></td>
</tr>
<tr>
<td>9.5 Vol %</td>
<td>81</td>
<td>36</td>
<td>0.81</td>
<td>81.4</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>42</td>
<td>0.86</td>
<td>63.5</td>
<td>1.7</td>
</tr>
<tr>
<td>CH₄</td>
<td>120</td>
<td>46</td>
<td>0.86</td>
<td>55.1</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>143</td>
<td>49</td>
<td>0.86</td>
<td>39.1</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>47</td>
<td>0.80</td>
<td>39.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

**TABLE 5.5**

5.1.2.2. Characterisation of Dust Dispersion

The steel explosion tube of the Hartmann apparatus was replaced by a perspex tube with a sealed top end. A high speed cine camera was used to film the dust dispersion characteristics of the Hartmann apparatus. An 'event mark' on the edge of the film was synchronised with the activation of the dust dispersion solenoid valve. It was established that the dust cloud reaches the ignition source within 60ms, and that dust dispersion is complete in less than 100ms, see Plate XIII.

5.1.2.3. Dust Explosion Tests

Cellulose dust explosions were undertaken in the Hartmann apparatus using the standard 'hot coil' and 'train of induction coil sparks' ignition procedures described in section 4.1.2.1. The results of these tests identified the most explosible cellulose dust concentration as 0.85 kg m⁻³, see Figures 19 and 20. This concentration was used in all subsequent cellulose dust explosion experiments in the Hartmann apparatus.
PLATE XIII: Dust Dispersion in the Hartmann Tube
The measured explosion parameters of cellulose dust explosions initiated by a train of induction coil sparks after preset ignition delays, \( t'_v \), are summarised in Table 5.6. The actual ignition delays, \( t_v \), were measured from the explosion pressure/time records, see Figure 10.

<table>
<thead>
<tr>
<th>DUST</th>
<th>( n )</th>
<th>( t'_v )</th>
<th>( t_v )</th>
<th>( P_o )</th>
<th>( P_{\text{max}} )</th>
<th>( (dP/dt)_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ms</td>
<td>ms</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa s⁻¹</td>
<td></td>
</tr>
<tr>
<td>0.85 kg m⁻³</td>
<td>5</td>
<td>9</td>
<td>102</td>
<td>34</td>
<td>0.86</td>
<td>34.6</td>
</tr>
<tr>
<td>Cellulose</td>
<td>6</td>
<td>32</td>
<td>107</td>
<td>39</td>
<td>0.85</td>
<td>32.1</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>50</td>
<td>110</td>
<td>37</td>
<td>0.83</td>
<td>31.7</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>75</td>
<td>110</td>
<td>37</td>
<td>0.88</td>
<td>31.1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>95</td>
<td>113</td>
<td>39</td>
<td>0.81</td>
<td>28.8</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>119</td>
<td>133</td>
<td>40</td>
<td>0.85</td>
<td>27.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>151</td>
<td>166</td>
<td>43</td>
<td>0.76</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>185</td>
<td>196</td>
<td>45</td>
<td>0.72</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>228</td>
<td>250</td>
<td>47</td>
<td>0.51</td>
<td>3.3</td>
</tr>
</tbody>
</table>

**TABLE 5.6.**

The influence of ignition delay, \( t'_v \), on the measured explosion parameters is shown in Figure 21. Note that no ignition occurred at \( t_v < 100 \text{ms} \), using this ignition procedure.

The explosibility characteristics of cellulose dust dispersed into the Hartmann tube were measured using discrete ignition sources. The results of tests using 200mJ fuse head ignition, and using 100J capacitive spark ignition are presented in Figures 22 and 23 respectively. No ignition occurred at \( t_v < 45 \text{ms} \) using these discrete ignition procedures. An ignition delay of \( \sim 70 \text{ms} \) resulted in the most severe explosion.
Comparative cellulose dust explosibility measurements obtained using sustained and discrete ignition procedures are summarised in Table 5.7.

<table>
<thead>
<tr>
<th>IGNITION SOURCE</th>
<th>n</th>
<th>( t_v )</th>
<th>( P_{\text{max}} )</th>
<th>((dP/dt)_{\text{max}})</th>
<th>( S_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Coil</td>
<td>25</td>
<td>80(^+)</td>
<td>0.77</td>
<td>34.2</td>
<td>0.20</td>
</tr>
<tr>
<td>100J Capacitor Spark</td>
<td>5</td>
<td>80</td>
<td>0.78</td>
<td>36.6</td>
<td>0.24</td>
</tr>
<tr>
<td>Induction Coil Sparks</td>
<td>10</td>
<td>100(^+)</td>
<td>0.79</td>
<td>29.2</td>
<td>0.20</td>
</tr>
<tr>
<td>100J Capacitor Spark</td>
<td>10</td>
<td>100</td>
<td>0.78</td>
<td>31.6</td>
<td>0.21</td>
</tr>
</tbody>
</table>

\( t_v \) was estimated from the pressure/time record

### TABLE 5.7.

Comparative tests on a range of industrial dusts were undertaken in the Hartmann apparatus using two alternative ignition procedures:

(i) the 'standard' continuous hot coil;
(ii) a discrete 100J capacitor spark activated at \( t_v = 80\text{ms} \).

\((dP/dt)_{\text{max}}\) measurements at the most explosible dust concentrations, as determined by the hot coil ignition tests, are presented in Table 5.8.
EXPLOSIBLE DUST | $t_v$ (ms) | $\frac{(dP/dt)_{max}}{\text{Hot Coil}}$ (MPa s$^{-1}$) | $\delta$ | $\frac{(dP/dt)_{max}}{\text{100J Spark}}$
---|---|---|---|---
Sodium Stearate | 163 | 11.5 | 20.4 | 1.77
Industrial Dust A | 155 | 1.5 | 4.9 | 3.27
Industrial Dust B | 132 | 4.0 | 6.7 | 1.68
Soya Flour | 110 | 2.8 | 4.2 | 1.50
Cornflour | 85 | 22.7 | 18.9 | 0.83
Benzene Sulphonamide | 83 | 7.9 | 8.5 | 1.07
Maize Starch | 81 | 30.8 | 28.5 | 0.92
Cellulose | 80 | 34.2 | 36.6 | 1.07
Saccharin | 69 | 19.2 | 13.6 | 0.71
Pharmaceutical Dust A | 68 | 19.7 | 12.1 | 0.61
Pharmaceutical Dust B | 63 | 13.8 | 8.2 | 0.59
Stearic Acid | 58 | 32.2 | 18.2 | 0.56
Industrial Dust C | 50 | 31.6 | 24.2 | 0.77
Sulphur | 45 | 21.2 | 11.5 | 0.54

**TABLE 5.8.**

Note that $\delta$ is defined as the ratio of the measured $(dP/dt)_{max}$ values:

$$\delta = \frac{(dP/dt)_{max}}{\text{100J spark ignition}}$$

$$\delta = \frac{(dP/dt)_{max}}{\text{hot coil ignition}}$$

Figure 24 shows the relation between $(dP/dt)_{max}$, $\delta$ and $t_v$ (hot coil ignition). During these experiments it was established that certain granular dusts could not be effectively ignited in the Hartmann Apparatus using a 100J spark, even at long ignition delays, whereas they would ignite and
explode using the hot coil ignition procedure. Ignition of such dusts appeared to result from the flames produced when the combustible dust settled on the hot coil.

5.1.3. The 1:1 Aspect Ratio Vertical Tube Apparatus

A series of gas and cellulose dust explosion tests similar to those reported in section 5.1.2. above were undertaken in the 1:1 aspect ratio vertical tube apparatus.

5.1.3.1. Gas Explosion Tests

Explosibility measurements of quiescent CH₄ and 70/30 CH₄/H₂ combustible gases mixed with air are presented in Figures 25 and 26, and the determined explosion parameters at the most explosible combustible gas concentrations are summarised in Table 5.9.

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION</th>
<th>Pₘₐₓ</th>
<th>(dP/dt)ₘₐₓ</th>
<th>Sₜₑₛ</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>9.5 Vol %</td>
<td>0.69</td>
<td>50</td>
<td>0.35</td>
</tr>
<tr>
<td>70/30 CH₄/H₂</td>
<td>14.5 Vol %</td>
<td>0.74</td>
<td>74</td>
<td>0.44</td>
</tr>
</tbody>
</table>

**TABLE 5.9.**

A typical pressure/time record of a quiescent combustible gas/air explosion in this 1:1 aspect ratio tube is compared with the corresponding record obtained in the Hartmann tube in Figure 18. A fully developed explosion is attained in this apparatus.
The results of turbulent 9.5 Vol % \( \text{CH}_4 \) and 14.5 Vol % 70/30 \( \text{CH}_4/\text{H}_2 \) explosions are presented in Table 5.10.

<table>
<thead>
<tr>
<th>GAS</th>
<th>( t_v )</th>
<th>( n )</th>
<th>( P_o )</th>
<th>( P_{\text{max}} )</th>
<th>( (\text{dP/dt})_{\text{max}} )</th>
<th>( \text{Tu} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{CH}_4 ) (9.5 Vol %)</td>
<td>70</td>
<td>2</td>
<td>30</td>
<td>0.78</td>
<td>207</td>
<td>3.51</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>5</td>
<td>31</td>
<td>0.85</td>
<td>150</td>
<td>2.51</td>
</tr>
<tr>
<td></td>
<td>115</td>
<td>4</td>
<td>31</td>
<td>0.88</td>
<td>175</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>135</td>
<td>5</td>
<td>34</td>
<td>0.89</td>
<td>130</td>
<td>2.14</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>6</td>
<td>34</td>
<td>0.90</td>
<td>108</td>
<td>1.77</td>
</tr>
<tr>
<td>( 70:30 \text{CH}_4:\text{H}_2 ) (14.5 Vol %)</td>
<td>75</td>
<td>1</td>
<td>25</td>
<td>0.91</td>
<td>342</td>
<td>4.32</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>3</td>
<td>28</td>
<td>0.83</td>
<td>274</td>
<td>3.38</td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>3</td>
<td>28</td>
<td>0.87</td>
<td>182</td>
<td>2.24</td>
</tr>
<tr>
<td></td>
<td>138</td>
<td>4</td>
<td>31</td>
<td>0.87</td>
<td>234</td>
<td>2.68</td>
</tr>
<tr>
<td></td>
<td>165</td>
<td>3</td>
<td>31</td>
<td>0.87</td>
<td>174</td>
<td>2.11</td>
</tr>
</tbody>
</table>

**TABLE 5.10.**

5.1.3.2. Dust Explosion Tests

Cellulose dust/air explosions were undertaken in this apparatus using induction spark ignition, see Figure 27. The most explosible concentration identified, 0.8kg m\(^{-3}\), was used in all subsequent cellulose dust tests in this apparatus. The measured explosibility of cellulose dust dispersions, ignited by a train of induction coil sparks after preset ignition delays, are presented in Table 5.11.
Figure 28 shows the influence of ignition delay on explosion parameters in this test apparatus.

Comparative results of cellulose dust explosion parameters determined with the alternative ignition procedures, a) the standard train of induction coil sparks, and b) the discrete 100J capacitive spark, are presented in Table 5.12.

<table>
<thead>
<tr>
<th>DUST</th>
<th>$t_v$ (ms)</th>
<th>$n$</th>
<th>$P_o$ (kPa)</th>
<th>$P_{max}$ (MPa)</th>
<th>$(dP/dt)_{max}$ (MPa s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80kg m$^{-3}$ Cellulose</td>
<td>100</td>
<td>10</td>
<td>20</td>
<td>0.77</td>
<td>37.8</td>
</tr>
<tr>
<td></td>
<td>121</td>
<td>5</td>
<td>22</td>
<td>0.86</td>
<td>37.9</td>
</tr>
<tr>
<td></td>
<td>135</td>
<td>5</td>
<td>24</td>
<td>0.86</td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>144</td>
<td>3</td>
<td>21</td>
<td>0.84</td>
<td>34.9</td>
</tr>
<tr>
<td></td>
<td>188</td>
<td>5</td>
<td>30</td>
<td>0.67</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>193</td>
<td>5</td>
<td>38</td>
<td>0.69</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td>254</td>
<td>5</td>
<td>38</td>
<td>0.51</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>301</td>
<td>5</td>
<td>39</td>
<td>0.39</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>373</td>
<td>5</td>
<td>39</td>
<td>0.16</td>
<td>1.0</td>
</tr>
</tbody>
</table>

TABLE 5.11.

<table>
<thead>
<tr>
<th>IGNITION SOURCE</th>
<th>$n$</th>
<th>$t_v$ (ms)</th>
<th>$P_{max}$ (MPa)</th>
<th>$(dP/dt)_{max}$ (MPa s$^{-1}$)</th>
<th>$S_u$ (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induction Coil Sparks</td>
<td>10</td>
<td>100</td>
<td>0.77</td>
<td>37.8</td>
<td>0.25</td>
</tr>
<tr>
<td>100J Capacitor Spark</td>
<td>6</td>
<td>100</td>
<td>0.83</td>
<td>38.7</td>
<td>0.23</td>
</tr>
<tr>
<td>100J Capacitor Spark</td>
<td>9</td>
<td>70</td>
<td>0.83</td>
<td>52.1</td>
<td>0.33</td>
</tr>
</tbody>
</table>

TABLE 5.12.
5.1.4. The 43 dm$^3$ Spherical Apparatus

5.1.4.1. Gas Explosions

Explosibility measurements of quiescent CH$_4$, 70/30 CH$_4$/H$_2$ and C$_3$H$_8$ combustible gases, mixed with air, are presented graphically in Figures 29 - 31. Table 5.13. summarises the measured explosibility parameters of the most explosible concentrations of these gases.

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION Vol %</th>
<th>$P_{\text{max}}$ MPa</th>
<th>$(dP/\text{dt})_{\text{max}}$ MPa s$^{-1}$</th>
<th>$S_u$ m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>10.5</td>
<td>0.69</td>
<td>17.6</td>
<td>0.29</td>
</tr>
<tr>
<td>70/30 CH$_4$/H$_2$</td>
<td>14.0</td>
<td>0.69</td>
<td>25.6</td>
<td>0.45</td>
</tr>
<tr>
<td>C$_3$H$_8$</td>
<td>4.5</td>
<td>0.80</td>
<td>34.0</td>
<td>0.46</td>
</tr>
</tbody>
</table>

TABLE 5.13.

Comparable unsuppressed quiescent gas explosion experiments were undertaken at the most explosible gas concentrations with capacitive spark ignition with spark energies ranging from 1.7J to 320J. These results are presented in Table 5.14.
<table>
<thead>
<tr>
<th>GAS</th>
<th>IGNITION SOURCE</th>
<th>IGNITION ENERGY</th>
<th>n</th>
<th>$P_{\text{max}}$</th>
<th>$(dP/dt)_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$J$</td>
<td></td>
<td>MPa</td>
<td>MPa s$^{-1}$</td>
</tr>
<tr>
<td>10.5 Vol %</td>
<td>Induction coil</td>
<td>0.03</td>
<td>7</td>
<td>0.69</td>
<td>17.6</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>40\mu F capacitor</td>
<td>100</td>
<td>5</td>
<td>0.69</td>
<td>15.2</td>
</tr>
<tr>
<td></td>
<td>40\mu F capacitor</td>
<td>320</td>
<td>3</td>
<td>0.66</td>
<td>13.3</td>
</tr>
<tr>
<td>14 Vol %</td>
<td>Induction coil</td>
<td>0.03</td>
<td>13</td>
<td>0.69</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td>1\mu F capacitor</td>
<td>1.7</td>
<td>2</td>
<td>0.73</td>
<td>25.5</td>
</tr>
<tr>
<td></td>
<td>1\mu F capacitor</td>
<td>6.8</td>
<td>2</td>
<td>0.74</td>
<td>26.8</td>
</tr>
<tr>
<td>70/30 CH$_4$/H$_2$</td>
<td>40\mu F capacitor</td>
<td>6.8</td>
<td>1</td>
<td>0.66</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td>40\mu F capacitor</td>
<td>100</td>
<td>1</td>
<td>0.70</td>
<td>21.5</td>
</tr>
<tr>
<td></td>
<td>40\mu F capacitor</td>
<td>180</td>
<td>2</td>
<td>0.68</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>40\mu F capacitor</td>
<td>320</td>
<td>2</td>
<td>0.68</td>
<td>17.7</td>
</tr>
<tr>
<td>4.5 Vol %</td>
<td>Induction coil</td>
<td>0.03</td>
<td>2</td>
<td>0.75</td>
<td>34.0</td>
</tr>
<tr>
<td>C$_3$H$_8$</td>
<td>40\mu F capacitor</td>
<td>100</td>
<td>2</td>
<td>0.80</td>
<td>25.0</td>
</tr>
</tbody>
</table>

**TABLE 5.14.**

There is an observed inverse correlation between the ignition energy and the measured $(dP/dt)_{\text{max}}$ values. The early part of the explosion pressure/time curves were influenced by the energy of the capacitive spark ignition source, see Figure 32.

The effect of induced turbulence on the explosion parameters of combustible gas concentrations in the 43 dm$^3$ apparatus is demonstrated by the results summarised in Table 5.15. These experiments were undertaken using the perforated spray ring dispersion procedure and induction coil spark ignition.
<table>
<thead>
<tr>
<th>GAS</th>
<th>$t_v$</th>
<th>$n$</th>
<th>$P_o$</th>
<th>$P_{max}$</th>
<th>$(dP/dt)_{max}$</th>
<th>$\alpha_{Su}$</th>
<th>$\alpha_{Tu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ms</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa s$^{-1}$</td>
<td>m s$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.5 Vol % CH$_4$</td>
<td>210</td>
<td>4</td>
<td>33</td>
<td>0.86</td>
<td>144</td>
<td>2.24</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>264</td>
<td>6</td>
<td>39</td>
<td>0.93</td>
<td>123</td>
<td>2.08</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>320</td>
<td>3</td>
<td>40</td>
<td>0.95</td>
<td>95</td>
<td>1.85</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>396</td>
<td>1</td>
<td>41</td>
<td>0.90</td>
<td>84</td>
<td>1.34</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>488</td>
<td>1</td>
<td>40</td>
<td>0.91</td>
<td>60</td>
<td>0.93</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>538</td>
<td>1</td>
<td>44</td>
<td>0.91</td>
<td>60</td>
<td>0.82</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>1</td>
<td>43</td>
<td>0.86</td>
<td>41</td>
<td>0.65</td>
<td>2.2</td>
</tr>
<tr>
<td>14 Vol % 70/30 CH$_4$/H$_2$</td>
<td>210</td>
<td>3</td>
<td>37</td>
<td>0.89</td>
<td>169</td>
<td>3.07</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>263</td>
<td>4</td>
<td>39</td>
<td>0.86</td>
<td>143</td>
<td>2.06</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>320</td>
<td>3</td>
<td>41</td>
<td>0.89</td>
<td>109</td>
<td>1.83</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>375</td>
<td>1</td>
<td>44</td>
<td>0.85</td>
<td>104</td>
<td>1.82</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>435</td>
<td>1</td>
<td>43</td>
<td>0.85</td>
<td>83</td>
<td>1.56</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>473</td>
<td>1</td>
<td>44</td>
<td>0.90</td>
<td>78</td>
<td>1.38</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>593</td>
<td>1</td>
<td>48</td>
<td>0.85</td>
<td>69</td>
<td>1.14</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>745</td>
<td>1</td>
<td>47</td>
<td>0.90</td>
<td>60</td>
<td>0.95</td>
<td>2.1</td>
</tr>
</tbody>
</table>

**TABLE 5.15.**

5.1.4.2. Dust Explosion Tests

The explosibility parameters of cellulose dust were measured in the prototype 43 dm$^3$ apparatus (1.8 dm$^3$ canister with 0.82 MPa dispersion pressure and pepper pot spreader disperser) using a train of induction coil sparks as the ignition source. The most explosible dust concentration was found to be 0.9 kg m$^{-3}$, see Figure 33. The resultant ignition delay with this dust dispersion procedure proved to be very long. Subsequent tests used a
$0.9 \text{ dm}^3$ dust dispersion canister pressurised to 1.64 MPa. Table 5.16 summarises the measured explosibility data with the two test procedures.

<table>
<thead>
<tr>
<th>DISPERSION PROCEDURE</th>
<th>n</th>
<th>$t_v$ (ms)</th>
<th>$P_o$ (kPa)</th>
<th>$P_{max}$ (MPa)</th>
<th>$(dP/dt)_{max}$ (MPa s$^{-1}$)</th>
<th>% no ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: 1.8 dm$^3$ canister, 0.82 MPa, pepper pot spreader</td>
<td>10</td>
<td>570</td>
<td>0.89</td>
<td>10.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B: 0.9 dm$^3$ canister, 1.64 MPa, pepper pot spreader</td>
<td>7</td>
<td>285</td>
<td>0.93</td>
<td>10.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 5.16.**

Tests were undertaken using dispersion procedure B and 100 J capacitor spark ignition and a cellulose dust concentration of $0.9 \text{ kg m}^{-3}$ in the $43 \text{ dm}^3$ apparatus. The explosion parameters measured at several preset ignition delay times are summarised in Table 5.17.

<table>
<thead>
<tr>
<th>DUST</th>
<th>n</th>
<th>$t_v$ (ms)</th>
<th>$P_o$ (kPa)</th>
<th>$P_{max}$ (MPa)</th>
<th>$(dP/dt)_{max}$ (MPa s$^{-1}$)</th>
<th>% no ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9kg m$^{-3}$</td>
<td>5</td>
<td>194</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>0.9kg m$^{-3}$</td>
<td>9</td>
<td>250</td>
<td>27</td>
<td>0.95</td>
<td>27.4</td>
<td>45</td>
</tr>
<tr>
<td>0.9kg m$^{-3}$</td>
<td>7</td>
<td>300</td>
<td>28</td>
<td>0.96</td>
<td>23.9</td>
<td>30</td>
</tr>
<tr>
<td>Cellulose</td>
<td>6</td>
<td>372</td>
<td>30</td>
<td>0.99</td>
<td>23.7</td>
<td>17</td>
</tr>
<tr>
<td>Cellulose</td>
<td>7</td>
<td>420</td>
<td>35</td>
<td>1.03</td>
<td>17.4</td>
<td>14</td>
</tr>
<tr>
<td>Cellulose</td>
<td>5</td>
<td>622</td>
<td>35</td>
<td>0.99</td>
<td>11.0</td>
<td>0</td>
</tr>
<tr>
<td>Cellulose</td>
<td>5</td>
<td>820</td>
<td>34</td>
<td>0.90</td>
<td>9.9</td>
<td>0</td>
</tr>
</tbody>
</table>

**TABLE 5.17.**
With the shorter ignition delay times some tests resulted in no ignition of the dust dispersion. Figure 34 shows the relation between the explosion parameters and the ignition delay, $t_v$.

A few experiments were undertaken to appraise the influence of the capacitor discharge ignition energy on the explosion severity of turbulent cellulose dust/air dispersions. The results obtained are presented in Table 5.18.

![Table 5.18](image)

Similarly a few experiments were undertaken with a higher dust dispersion pressure of 20.5 MPa using the same 'pepper pot' dust dispersion system, see Table 5.19.

![Table 5.19](image)
A high speed film of the 'pepper pot' dust dispersion procedure, obtained using a 40 dm$^3$ spherical glass flask to simulate the test vessel, showed that all of the dust was effectively ejected in less than 200ms; but that the 'pepper pot' did not disperse the dust sample homogeneously into the sphere. The semi-circular perforated spray pipe produced a more homogeneous dust dispersion in the test vessel. The dust sample was dispersed through this spray pipe in ~210ms. The influence of ignition delay time, $t_v$, on the measured explosibility of 0.9kg m$^{-3}$ cellulose dust was evaluated using this semi-circular spray ring dispersion procedure and 100J capacitor spark ignition, see Table 5.20.

<table>
<thead>
<tr>
<th>DUST</th>
<th>$t_v$ (ms)</th>
<th>$n$</th>
<th>$P_{max}$ (MPa)</th>
<th>$(dP/dt)_{max}$ (MPa s$^{-1}$)</th>
<th>$\alpha S_u$ (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9kg m$^{-3}$ Cellulose</td>
<td>90</td>
<td>3</td>
<td>0.86</td>
<td>46.1</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>115</td>
<td>1</td>
<td>0.93</td>
<td>54.1</td>
<td>1.43</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>3</td>
<td>0.99</td>
<td>59.5</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>6</td>
<td>0.98</td>
<td>45.5</td>
<td>1.26</td>
</tr>
<tr>
<td></td>
<td>265</td>
<td>4</td>
<td>0.98</td>
<td>36.7</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>320</td>
<td>2</td>
<td>0.93</td>
<td>36.1</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>437</td>
<td>3</td>
<td>0.97</td>
<td>24.7</td>
<td>0.79</td>
</tr>
</tbody>
</table>

**TABLE 5.20.**

Effective ignition was achieved for all $t_v > 90$ms with this spray ring dust dispersion procedure. The relations between $t_v$ and both $(dP/dt)_{max}$ and $S_u$ are shown in Figure 35. Cellulose dust explosion tests were undertaken with an ignition delay equal to the dust dispersion time in the 43 dm$^3$
apparatus (\(t_v = 210\text{ms}\)) over a range of dust concentrations. These tests, see Figure 36, verified that 0.9 kg m\(^{-3}\) was the most exploisible concentration of cellulose dust in this test apparatus.

The spray ring dust dispersion methodology described for the 43 dm\(^3\) apparatus generates an initial overpressure in the vessel, at ignition of \(\sim 28\) kPa, which is comparable with that produced in the Hartmann apparatus. Test results in the 43 dm\(^3\) apparatus using spray ring dispersion with a lower dust dispersion pressure, and also with partial evacuation of the explosion chamber, such that the dust explosion was initiated at atmospheric pressure, are presented in Table 5.21. These tests were undertaken with the optimum ignition delay of 210 ms and 100 J capacitive spark ignition.

<table>
<thead>
<tr>
<th>DUST</th>
<th>CONCENTRATION kg m(^{-3})</th>
<th>DISPERSION PRESSURE MPa</th>
<th>(n)</th>
<th>(P_o) kPa</th>
<th>(P_{max}) MPa</th>
<th>((dP/dt)_{ma}) MPa s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>0.9</td>
<td>1.64</td>
<td>6</td>
<td>28</td>
<td>0.98</td>
<td>45.5</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>0.82</td>
<td>5</td>
<td>14</td>
<td>0.89</td>
<td>36.6</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>1.64</td>
<td>5</td>
<td>0</td>
<td>0.86</td>
<td>34.3</td>
</tr>
<tr>
<td></td>
<td>0.78</td>
<td>1.64</td>
<td>4</td>
<td>0</td>
<td>0.82</td>
<td>33.7</td>
</tr>
<tr>
<td></td>
<td>0.66</td>
<td>1.64</td>
<td>4</td>
<td>0</td>
<td>0.83</td>
<td>32.0</td>
</tr>
</tbody>
</table>

**TABLE 5.21.**

The explosion parameters of five dusts, determined at their most exploisible concentrations in the 43 dm\(^3\) apparatus using the spray ring dispersion procedure and 100 J spark ignition are summarised in Table 5.22. These tests were undertaken at three discrete ignition delays (turbulence levels). Each result is an average of five measurements.
TABLE 5.22.

<table>
<thead>
<tr>
<th>DUST</th>
<th>$(\frac{dP}{dt})_{\text{max}}$</th>
<th>$(MPa \ s^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t_v = 210ms$</td>
<td>$t_v = 265ms$</td>
</tr>
<tr>
<td>Gum Arabic</td>
<td>35.8</td>
<td>27.2</td>
</tr>
<tr>
<td>Magnesium Stearate</td>
<td>90.4</td>
<td>77.6</td>
</tr>
<tr>
<td>Phenolic Resin</td>
<td>64.3</td>
<td>56.4</td>
</tr>
<tr>
<td>Fenclofenac</td>
<td>31.6</td>
<td>30.2</td>
</tr>
<tr>
<td>Cellulose</td>
<td>45.5</td>
<td>36.6</td>
</tr>
</tbody>
</table>

5.1.5. The 6.2m$^3$ IEP Test Vessel

5.1.5.1. Gas Explosion Tests

Quiescent CH$_4$, 70/30 CH$_4$/H$_2$, and C$_3$H$_8$ gas explosions were undertaken in this large volume chamber using spark ignition.

It was noted that the pressure/time curves of quiescent CH$_4$ - air explosions exhibited a doublet of the form shown below:
This doublet was more distinct at specific CH\textsubscript{4} concentrations and the pressure record had an imposed oscillation. In general, \((dP/dt)_{\text{max}}^+ > (dP/dt)_{\text{max}}^-\). The results of quiescent CH\textsubscript{4} - air explosions ignited with a 30mJ induction coil spark are summarised in Table 5.23.

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION P\textsubscript{max}</th>
<th>(dP/dt)\textsubscript{max}^-</th>
<th>(dP/dt)\textsubscript{max}^+</th>
<th>S\textsubscript{u}^-</th>
<th>S\textsubscript{u}^+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol %</td>
<td>MPa</td>
<td>MPa s\textsuperscript{-1}</td>
<td>MPa s\textsuperscript{-1}</td>
<td>m s\textsuperscript{-1}</td>
</tr>
<tr>
<td>CH\textsubscript{4}</td>
<td>6.7</td>
<td>0.4</td>
<td>0.5</td>
<td>-</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>0.61</td>
<td>1.60</td>
<td>-</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>-</td>
<td>2.90</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>-</td>
<td>4.50</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.6</td>
<td>0.64</td>
<td>-</td>
<td>2.95</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>-</td>
<td>3.15</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>0.65</td>
<td>-</td>
<td>2.40</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>-</td>
<td>2.40</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.63</td>
<td>1.75</td>
<td>2.95</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.68</td>
<td>2.35</td>
<td>2.50</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9.4</td>
<td>0.71</td>
<td>2.60</td>
<td>-</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>0.71</td>
<td>2.70</td>
<td>-</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td>2.70</td>
<td>-</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.73</td>
<td>2.73</td>
<td>3.70</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11.1</td>
<td>0.65</td>
<td>2.00</td>
<td>2.10</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>11.5</td>
<td>0.68</td>
<td>1.98</td>
<td>2.70</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>11.9</td>
<td>0.67</td>
<td>2.04</td>
<td>3.72</td>
<td>0.27</td>
</tr>
</tbody>
</table>

**TABLE 5.23.**
The results of comparable quiescent CH\textsubscript{4} - air explosions ignited with a 100J capacitive spark are summarised in Table 5.24.

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION</th>
<th>P\textsubscript{max}</th>
<th>(dP/dt)\textsubscript{max}</th>
<th>(dP/dt)\textsuperscript{+}\textsubscript{max}</th>
<th>S\textsubscript{u}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol %</td>
<td>(MPa)</td>
<td>(MPa s\textsuperscript{-1})</td>
<td>(MPa s\textsuperscript{-1})</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH\textsubscript{4}</td>
<td>6.4</td>
<td>0.49</td>
<td>0.49</td>
<td>-</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>7.0</td>
<td>0.51</td>
<td>0.90</td>
<td>-</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>7.6</td>
<td>0.63</td>
<td>0.98</td>
<td>2.27</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.61</td>
<td>0.65</td>
<td>2.55</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.55</td>
<td>1.00</td>
<td>1.97</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.63</td>
<td>0.95</td>
<td>2.32</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>0.61</td>
<td>1.73</td>
<td>1.45</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.57</td>
<td>1.30</td>
<td>-</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>9.4</td>
<td>0.64</td>
<td>2.45</td>
<td>-</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.67</td>
<td>2.27</td>
<td>-</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>9.8</td>
<td>0.67</td>
<td>2.65</td>
<td>-</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.73</td>
<td>3.05</td>
<td>-</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>10.2</td>
<td>0.69</td>
<td>2.80</td>
<td>2.77</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.69</td>
<td>3.10</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>10.6</td>
<td>0.71</td>
<td>2.80</td>
<td>3.60</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>11.1</td>
<td>0.67</td>
<td>2.40</td>
<td>-</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>11.9</td>
<td>0.65</td>
<td>2.07</td>
<td>-</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>12.3</td>
<td>0.59</td>
<td>1.18</td>
<td>-</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>12.8</td>
<td>0.55</td>
<td>0.73</td>
<td>-</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**TABLE 5.24.**
The data of Tables 5.23 and 5.24, ignoring the artefact of the doublet, are presented graphically in Figure 37. The explosion parameters of quiescent CH₄ - air can be ascertained from these results - see Table 5.25.

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION</th>
<th>P_max</th>
<th>(dP/dt)_max</th>
<th>S_u</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol %</td>
<td>MPa</td>
<td>MPa s⁻¹</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>CH₄</td>
<td>10.2</td>
<td>0.72</td>
<td>3.1</td>
<td>0.34</td>
</tr>
</tbody>
</table>

**TABLE 5.25.**

Note that this 'most explosible' concentration does not exhibit the distinct doublet which occurs at a concentration of 7.6 Vol. %.

Quiescent 70/30 CH₄/H₂ air explosions were studied in the 6.2m³ vessel using induction coil spark ignition only. These tests identified a more pronounced 'doublet', again at specific fuel gas concentrations. A (dP/dt)_max measurement could not be meaningfully measured from such curves because the perturbation occurred at ~ 0.3 MPa; but S_u could be ascertained.

Quiescent 70/30 CH₄/H₂ air explosion results are summarised in Table 5.26.

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION</th>
<th>P_max</th>
<th>(dP/dt)_max</th>
<th>(dP/dt)+_max</th>
<th>S_u</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol %</td>
<td>MPa</td>
<td>MPa s⁻¹</td>
<td>MPa s⁻¹</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>70/30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₄/H₂</td>
<td>9.9</td>
<td>0.56</td>
<td>2.9</td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>10.4</td>
<td>0.66</td>
<td>-</td>
<td>7.6</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>10.9</td>
<td>0.67</td>
<td>-</td>
<td>9.6</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>11.8</td>
<td>0.72</td>
<td>-</td>
<td>9.1</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>12.3</td>
<td>0.67</td>
<td>4.3</td>
<td>-</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>12.8</td>
<td>0.70</td>
<td>-</td>
<td>6.8</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>13.8</td>
<td>0.70</td>
<td>5.0</td>
<td>-</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>14.8</td>
<td>0.76</td>
<td>5.2</td>
<td>-</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>15.8</td>
<td>0.78</td>
<td>-</td>
<td>2.1</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>16.8</td>
<td>0.72</td>
<td>-</td>
<td>6.4</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>17.8</td>
<td>0.69</td>
<td>3.5</td>
<td>-</td>
<td>0.34</td>
</tr>
</tbody>
</table>

**TABLE 5.26.**
These data are presented graphically in Figure 38. The explosion parameters of 70/30 CH$_4$/H$_2$, ignoring the artefact of the doublet, can be estimated from these data – see Table 5.27.

<table>
<thead>
<tr>
<th>GAS CONCENTRATION</th>
<th>$P_{\text{max}}$</th>
<th>$(dP/dt)_{\text{max}}$</th>
<th>$S_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>70/30 CH$_4$/H$_2$</td>
<td>15</td>
<td>0.78</td>
<td>5.2</td>
</tr>
</tbody>
</table>

**TABLE 5.27.**

Quiescent C$_3$H$_8$ - air explosions were studied in the 6.2m$^3$ vessel using induction coil spark ignition. It was found that the explosion pressure/time records exhibited a marked transition at $(P_\gamma, t_\gamma)$ for all concentrations $\geq 4.5$ Vol %, and that the subsequent pressure record was violently oscillatory – see sketch below:

The pressure/time record of a 4.3 Vol % C$_3$H$_8$ mixture exhibited a 'doublet' of the type observed with some CH$_4$ and 70/30 CH$_4$/H$_2$ gas explosions. The results of C$_3$H$_8$ - Air explosions are presented in Table 5.28 and Figure 39.
### TABLE 5.28.

The explosion parameters of C\(_3\)H\(_8\) gas in the 6.2m\(^3\) vessel can be ascertained from these data – see Table 5.29.

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION</th>
<th>(P_{max})</th>
<th>((dP/dt)_{max})</th>
<th>(P_{t})</th>
<th>(S_u)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol %</td>
<td>MPa</td>
<td>MPa s(^{-1})</td>
<td>MPa s</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>(C_3H_8)</td>
<td>2.8</td>
<td>0.60</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>0.73</td>
<td>2.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3.8</td>
<td>0.78</td>
<td>4.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td>0.82</td>
<td>5.4</td>
<td>0.55</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>0.83</td>
<td>10.6</td>
<td>0.42</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>4.6</td>
<td>0.81</td>
<td>11.9</td>
<td>0.36</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>0.86</td>
<td>14.9</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>0.86</td>
<td>19.8</td>
<td>0.14</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>0.80</td>
<td>10.0</td>
<td>0.13</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td>0.78</td>
<td>11.0</td>
<td>0.14</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>6.6</td>
<td>0.64</td>
<td>4.2</td>
<td>0.15</td>
<td>3.10</td>
</tr>
</tbody>
</table>

### TABLE 5.29.

Note that the maximum \((dP/dt)_{max}\) value and the maximum \(S_u\) value occur at different \(C_3H_8\) concentrations.
The course of fireball growth was determined using a multi-probe flame proximity detector shown in plate XII, and from high speed cine records of the quiescent gas explosions. Fireball growth was of the form shown below:

Note that there is a finite time delay between ignition and propagation of the fireball away from the igniting electrodes. The fireball starts to grow out as a sphere, and then grows as an ellipsoid. The measured actual flame speeds, $S'_f$, are summarised in Table 5.30 below:

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION Vol %</th>
<th>$P_{max}$ MPa</th>
<th>$(dP/dt)_{max}$ MPa s$^{-1}$</th>
<th>$S_u$ m s$^{-1}$</th>
<th>$S'_f$ - AXIAL m s$^{-1}$</th>
<th>$S'_f$ - RADIAL m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{CH}_4$</td>
<td>7.6</td>
<td>0.64</td>
<td>2.90</td>
<td>0.18</td>
<td>2.6</td>
<td>1.4</td>
</tr>
<tr>
<td>$\text{CH}_4$</td>
<td>10.2</td>
<td>0.71</td>
<td>2.70</td>
<td>0.35</td>
<td>5.7</td>
<td>3.7</td>
</tr>
<tr>
<td>$\text{C}_3\text{H}_8$</td>
<td>4.6</td>
<td>0.81</td>
<td>11.90</td>
<td>0.43</td>
<td>4.9</td>
<td>3.4</td>
</tr>
</tbody>
</table>

**TABLE 5.30.**

The 6.2m$^3$ pressure vessel was fitted with strain gauges adjacent to the central pressure transducer to monitor the radial and hoop strains which occur in the vessel walls during quiescent gas explosions. It was found that there was only minimal axial and hoop strain with a 10.2 Vol % $\text{CH}_4$
explosion, but that there was a major axial strain with a 7.6 Vol % CH\textsubscript{4} explosion. This latter CH\textsubscript{4} concentration exhibited the 'doublet' artefact reported above. The pressure, fireball growth and strain gauge outputs superimposed on the same time axes are presented in Figure 40.

The theoretical burning velocity calculated from the pressure/time record, \( S_u \), see section 3.1.1., refers to a confined explosion centrally ignited in a closed sphere. The actual burning velocity in a non-spherical vessel is, from equations 15 and 17:

\[
\overline{S}_u = S_u \frac{r}{u^3} \cdot \frac{A}{V} \tag{42}
\]

\( \overline{S}_u \) is a vector average of the axial and radial burning velocities. The theoretical flame speed, \( S_f \), is given by equation 9:

\[
S_f = E \cdot S_u \tag{9}
\]

For CH\textsubscript{4} and C\textsubscript{3}H\textsubscript{8}, \( E \approx 7.7 \). Table 5.31 compares the theoretical average burning velocity \( \overline{S}_u \) with the corresponding average burning velocity \( \overline{S}'_u \) calculated from the measured axial and radial flame speeds \( S'_f \).

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION</th>
<th>DIRECTION</th>
<th>MEASURED</th>
<th>THEORETICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol %</td>
<td></td>
<td>( S'_f )</td>
<td>( S'_u )</td>
</tr>
<tr>
<td>CH\textsubscript{4}</td>
<td>10.2</td>
<td>AXIAL</td>
<td>4.9</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RADIAL</td>
<td>3.4</td>
<td>0.44</td>
</tr>
<tr>
<td>CH\textsubscript{4}</td>
<td>7.6</td>
<td>AXIAL</td>
<td>2.6</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RADIAL</td>
<td>1.4</td>
<td>0.18</td>
</tr>
<tr>
<td>C\textsubscript{3}H\textsubscript{8}</td>
<td>4.6</td>
<td>AXIAL</td>
<td>5.7</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RADIAL</td>
<td>3.7</td>
<td>0.48</td>
</tr>
</tbody>
</table>

TABLE 5.31.
5.1.5.2. Dust Explosion Tests

Cellulose dust explosions were undertaken in the 6.2 m$^3$ vessel using the experimental procedure described in section 4.4.5.3. An ignition delay of 970 ms was chosen to ascertain the most explosible cellulose dust concentration in this test apparatus, since this ignition delay is longer than the measured time interval of 860 ms required to expel the total dust charge into the container. Figure 41 shows that the optimum cellulose dust concentration was $\sim 0.73$ kg m$^{-3}$. The influence of ignition delay, $t_v$, on the measured explosion parameters of this most explosible dust concentration was evaluated. All tests used 100 J capacitive spark ignition. The results are summarised in Table 5.32. and Figure 42.

<table>
<thead>
<tr>
<th>DUST</th>
<th>$t_v$</th>
<th>$P_o$</th>
<th>$P_{max}$</th>
<th>$(dP/dt)_{max}$</th>
<th>$S_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ms</td>
<td>kPa</td>
<td>MPa</td>
<td>MPa s$^{-1}$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>.73 kg m$^{-3}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cellulose</td>
<td>282</td>
<td>4</td>
<td>No Ignition</td>
<td>16.0</td>
<td>1.96</td>
</tr>
<tr>
<td>(Batch WM)</td>
<td>425</td>
<td>6</td>
<td>0.87</td>
<td>11.8</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>660</td>
<td>6</td>
<td>0.90</td>
<td>9.8</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>860</td>
<td>7</td>
<td>0.89</td>
<td>7.8</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>980</td>
<td>6</td>
<td>0.88</td>
<td>4.9</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>1180</td>
<td>6</td>
<td>0.84</td>
<td>3.1</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>1380</td>
<td>8</td>
<td>0.82</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 5.32.**

The available supply of the original batch of cellulose dust (WM), see section 4.1.6.2., was exhausted in these trials. A second batch of cellulose dust with the same specification (WM2) was purchased for
subsequent tests in the 6.2m³ vessel. Repeated tests with this batch at the 'optimum' ignition delay of 860ms demonstrated that the explosion data measured in the 6.2m³ vessel was very reproducible; see Table 5.33.; and that the explosibility of Batch WM2 was ~25% more violent than had been found for batch WM, compare Tables 5.32. and 5.33.

<table>
<thead>
<tr>
<th>DUST</th>
<th>t_v</th>
<th>P_max</th>
<th>(dP/dt)_max</th>
<th>S_u</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ms</td>
<td>MPa</td>
<td>MPa s⁻¹</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>0.73kg m⁻³</td>
<td>860</td>
<td>0.89</td>
<td>10.75</td>
<td>1.26</td>
</tr>
<tr>
<td>Cellulose</td>
<td></td>
<td>0.90</td>
<td>11.40</td>
<td>1.15</td>
</tr>
<tr>
<td>(Batch WM2)</td>
<td></td>
<td>0.92</td>
<td>11.60</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.91</td>
<td>10.80</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.88</td>
<td>9.45</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.02</td>
<td>11.30</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.98</td>
<td>11.70</td>
<td>1.43</td>
</tr>
</tbody>
</table>

TABLE 5.33.

The cellulose dust batch WM2 was used in all explosion suppression trials in the 6.2m³ vessel described in section 5.4.33.
5.2. Explosion Suppressants

Cellulose dust explosions were undertaken in the Hartmann vertical tube apparatus in the presence of defined concentrations of suppressants using the experimental procedures described in section 4.2. The following agents were studied:

(i) carbon dioxide and nitrogen, see Figure 43;

(ii) Halon 1211 and Halon 1301\(^+\), see Figure 44;

(iii) mono-ammonium phosphate and china clay, see Figure 45.

Note that each point plotted in Figures 43 - 45 represents an average of at least five measurements. The determined minimum inhibiting concentration of these agents, for cellulose dust dispersions, are summarised in Table 5.34.

<table>
<thead>
<tr>
<th>SUPPRESSANT AGENT</th>
<th>INHIBITING CONCENTRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>42 Vol %</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>51 Vol %</td>
</tr>
<tr>
<td>Halon 1211</td>
<td>7.4 Vol %</td>
</tr>
<tr>
<td>Halon 1301</td>
<td>7.6 Vol %</td>
</tr>
<tr>
<td>Mono-ammonium Phosphate</td>
<td>27 weight % (0.25kg m(^{-3}))</td>
</tr>
<tr>
<td>China Clay</td>
<td>69 weight % (0.65kg m(^{-3}))</td>
</tr>
</tbody>
</table>

**TABLE 5.34.**

+ Note that Halon 1211 and Halon 1301 are vapours at NTP.
5.3. Explosion Suppressors

The suppressant discharge characteristics of Graviner hemispherical and high rate discharge (HRD) explosion suppressors were measured and are presented below.

5.3.1. Hemispherical Suppressors

The discharge of a 1 dm$^3$ capacity Halon 1011 hemispherical suppressor against a background squared grid (300mm) is shown in Plate XIV. Study of the high speed film records indicates that this type of suppressor opens within 1ms, and discharges its contents over a 180° solid angle with an initial discharge velocity in excess of 100 m s$^{-1}$.

The discharge characteristics of 0.5 dm$^3$, 1.0 dm$^3$ and 5.0 dm$^3$ hemispherical suppressors, charged with Halon 1011, were determined from high speed films of the discharge event and are shown in Figure 46.

5.3.2. High Rate Discharge (HRD) Suppressors

5.3.2.1. Standard Graviner HRD Suppressors

The discharge of a 3 dm$^3$ HRD suppressor, with elbow and 75mm long spreader, against a background (300mm) squared grid is shown in Plate XV. A close study of the film records indicates that an initial burst of Halon is observed some 5ms after firing, and that the bulk discharge does not start until ~18ms after firing. The measured discharge velocity was ~ 43 m s$^{-1}$. The U.V. oscillograph output record, see section 4.3.3., for this 3 dm$^3$ HRD suppressor is shown in Figure 47. Canister depressurisation, which commences after ~7ms is completed in ~125ms. The maximum rate of depressurisation is 109 MPa s$^{-1}$. The oscillograph output had curves from two separate strain gauge networks mounted on the spreader:

* The standard nomenclature describes an HRD suppressor by its suppressant charge.
PLATE XIV: Discharge Characteristic of 1dm³ Hemispherical Suppressor
The more sensitive $\text{SG}_1$ system identified both an initial burst and, a bulk discharge of suppressant. This $\text{SG}_1$ system, however, proved to be very unreliable because the strain gauges mounted on the inner surface of the spreader assembly were frequently damaged by copper fragments from the detonator and the frangible disc. The $\text{SG}_2$ system, although much less sensitive, proved very reliable. However, the output from the $\text{SG}_2$ system was confounded by temperature effects, which produced a zero shift during the discharge event. Initial tests were carried out with both strain gauge systems, but the inherent unreliability of the $\text{SG}_1$ system delayed tests to such an extent that subsequent discharge experiments were undertaken with only the $\text{SG}_2$ system operational. The following parameters were defined from these strain gauge outputs:

![Diagram]

- $t_0^\prime$ - start of initial burst of suppressant
- $t_0$ - start of bulk discharge
- $t_1$ - end of bulk discharge
- $t_2$ - completion of discharge
- $R_1$ - estimated average mass discharge rate between $t_0$ and $t_2$ (bulk discharge).
- $R_2$ - estimated average mass discharge rate between $t_1$ and $t_2$. 

(i) \( \text{SG}_1 \) – full bridge strain gauge network;
(ii) \( \text{SG}_2 \) – single arm strain gauge network.
PLATE XV: Discharge Characteristic of 3dm$^3$ HRD Suppressor
The results of suppressor discharge tests, using standard Graviner and Deugra single exit (76mm diameter) HRD suppressor systems, are summarised in Tables 5.35 - 5.37.

**HALON 1011 SYSTEMS - $P_{N_2} = 2$ MPa**

<table>
<thead>
<tr>
<th>SUPPRESSANT CAPACITY dm³</th>
<th>ELBOW</th>
<th>SPREADER LENGTH mm</th>
<th>$t_0'$</th>
<th>$t_o$</th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>$R_1$</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>No</td>
<td>75</td>
<td>-</td>
<td>9</td>
<td>25</td>
<td>100</td>
<td>142</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>75</td>
<td>3.5</td>
<td>17</td>
<td>39</td>
<td>113</td>
<td>104</td>
<td>46</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>150</td>
<td>-</td>
<td>18</td>
<td>56</td>
<td>128</td>
<td>80</td>
<td>43</td>
</tr>
<tr>
<td>10</td>
<td>Yes</td>
<td>150</td>
<td>-</td>
<td>16</td>
<td>77</td>
<td>220</td>
<td>125</td>
<td>80</td>
</tr>
<tr>
<td>35</td>
<td>Yes</td>
<td>150</td>
<td>-</td>
<td>18</td>
<td>220</td>
<td>1370</td>
<td>89</td>
<td>44</td>
</tr>
</tbody>
</table>

**TABLE 5.35.**

**WATER SYSTEMS - $P_{N_2} = 2$ MPa**

<table>
<thead>
<tr>
<th>SUPPRESSANT CAPACITY dm³</th>
<th>ELBOW</th>
<th>SPREADER LENGTH mm</th>
<th>$t_0'$</th>
<th>$t_o$</th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>$R_1$</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Yes</td>
<td>75</td>
<td>5</td>
<td>12</td>
<td>31</td>
<td>83</td>
<td>63</td>
<td>35</td>
</tr>
<tr>
<td>10</td>
<td>Yes</td>
<td>150</td>
<td>-</td>
<td>12</td>
<td>80</td>
<td>220</td>
<td>59</td>
<td>42</td>
</tr>
<tr>
<td>35</td>
<td>Yes</td>
<td>150</td>
<td>-</td>
<td>11</td>
<td>198</td>
<td>951</td>
<td>66</td>
<td>30</td>
</tr>
</tbody>
</table>

**TABLE 5.36.**
POWDER SYSTEM - $P_{N_2} = 6$ MPa

<table>
<thead>
<tr>
<th>SUPPRESSANT CAPACITY</th>
<th>ELBOW</th>
<th>SPREADER LENGTH</th>
<th>$t'_0$</th>
<th>$t_0$</th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>$R_1$</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>dm$^3$</td>
<td>mm</td>
<td>ms</td>
<td>ms</td>
<td>ms</td>
<td>ms</td>
<td>ms</td>
<td>kg s$^{-1}$</td>
<td>kg s$^{-1}$</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>150</td>
<td>-</td>
<td>9</td>
<td>23</td>
<td>110</td>
<td>110</td>
<td>32</td>
</tr>
</tbody>
</table>

TABLE 5.37.

The measured discharge profiles of single exit (76 mm diameter) HRD suppressors are shown in Figure 48.

5.3.2.2. Influence of Fill Ratio

A series of Halon 1011 discharge tests were undertaken using different fill ratios in the standard 3 dm$^3$ HRD suppressor (actual canister volume ~ 5 dm$^3$) with elbow and 75 mm long spreader. The results obtained are presented in Table 5.38.

<table>
<thead>
<tr>
<th>SUPPRESSANT CAPACITY</th>
<th>FILL RATIO</th>
<th>$t'_0$</th>
<th>$t_0$</th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>$R_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>dm$^3$</td>
<td>ms ms ms ms</td>
<td>kg s$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>0.32</td>
<td>13</td>
<td>28</td>
<td>90</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>0.50</td>
<td>4</td>
<td>15</td>
<td>37</td>
<td>98</td>
<td>103</td>
</tr>
<tr>
<td>3.0</td>
<td>0.60</td>
<td>3.5</td>
<td>17</td>
<td>39</td>
<td>113</td>
<td>104</td>
</tr>
<tr>
<td>3.5</td>
<td>0.70</td>
<td>5</td>
<td>15</td>
<td>49</td>
<td>138</td>
<td>84</td>
</tr>
</tbody>
</table>

TABLE 5.38
The influence of the fill ratio on the bulk \((t_1 - t_0)\) and the total \((t_2 - t_0)\) discharge times are shown in Figure 49. Constant discharge rate lines are superimposed over the experimental curves in Figure 49 (a) and (b).

Canister depressurisation curves for this series of experiments are presented in Figure 50. The initial discharge velocities determined from the film records of these tests were very similar \(\sim 43 \text{ m s}^{-1}\). It was evident from measurements of the strain gauge network outputs that the percentage of the total suppressant capacity discharged between \(t_0\) and \(t_1\), bulk discharge regime, was essentially constant at \(\sim 40\%\) for suppressant fill ratios from 0.32 to 0.7.

5.3.2.3. Influence of Propelling Agent Pressure \(P_{N_2}\)

Comparable discharge tests were undertaken at three different propelling agent pressures using the standard 3 dm\(^3\) HRD suppressor with elbow and 75mm long spreader. The results obtained are presented in Table 5.39.

<table>
<thead>
<tr>
<th>PROPELLING AGENT PRESSURE MPa</th>
<th>(t_0) ms</th>
<th>(t_0) ms</th>
<th>(t_1) ms</th>
<th>(t_2) ms</th>
<th>(R_1) kg s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.35</td>
<td>4</td>
<td>19</td>
<td>42</td>
<td>120</td>
<td>99</td>
</tr>
<tr>
<td>2.0</td>
<td>3.5</td>
<td>17</td>
<td>39</td>
<td>113</td>
<td>104</td>
</tr>
<tr>
<td>3.1</td>
<td>3</td>
<td>14</td>
<td>35</td>
<td>100</td>
<td>109</td>
</tr>
</tbody>
</table>

TABLE 5.39.
The influence of the propelling agent pressure, $P_{N_2}$, on the bulk ($t_1 - t_o$) and the total ($t_2 - t_o$) discharge times, and on the bulk discharge rate ($R_1$) are shown in Figure 51. Measurement from the high speed films of the suppressant throw 50ms after firing the suppressors, gave results of 1.82m, 1.85m and 2.20m for propelling agent pressures of 1.35, 2.0 and 3.1 MPa respectively.

5.3.2.4. Influence of Outlet Orifice Area

Comparable discharge tests were undertaken with reduced orifice areas using the same standard 3 dm$^3$ HRD suppressor with elbow and 75mm long spreader. The orifice area was reduced by inserting a copper annulus between the frangible disc and the suppressor canister head assembly. In these tests the presence of the annulus did not impede the effective rupture of the frangible disc. The results are presented in Table 5.40.

<table>
<thead>
<tr>
<th>OUTLET ORIFICE DIA.</th>
<th>OUTLET ORIFICE AREA</th>
<th>$t_1$</th>
<th>$t_0$</th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>% DISCHARGE (bulk)</th>
<th>$R_1$ kg s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>m$^3$</td>
<td>ms</td>
<td>ms</td>
<td>ms</td>
<td>ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>0.0181</td>
<td>3.5</td>
<td>17</td>
<td>39</td>
<td>113</td>
<td>40</td>
<td>104</td>
</tr>
<tr>
<td>63.5</td>
<td>0.0126</td>
<td>5</td>
<td>14</td>
<td>62</td>
<td>120</td>
<td>55</td>
<td>65</td>
</tr>
<tr>
<td>51</td>
<td>0.0082</td>
<td>3</td>
<td>15</td>
<td>110</td>
<td>140</td>
<td>80</td>
<td>48</td>
</tr>
</tbody>
</table>

TABLE 5.40
It was evident from measurements of the strain gauge network outputs that the percentage of the total suppressant capacity that was discharged between $t_0$ and $t_1$, bulk discharge regime, increased with reducing orifice area; but the suppressant discharge time increased. These percentages of suppressant discharged were estimated and are included in the Table 5.40.

The influence of outlet orifice size on the discharge times and the bulk discharge rates are shown in Figure 52. The corresponding canister depressurisation curves are presented in Figure 50. The initial suppressant discharge velocities measured from high speed film records of the discharges were in the range $42 - 45 \text{ m s}^{-1}$.

5.4. Explosion Suppression

The results of explosion suppression trials undertaken in the $1 \text{m}^3$ and $6.2 \text{ m}^3$ test vessels are presented below. Computer estimates of the suppressed explosion pressures, based on the theoretical model of explosion suppression described in section 3.4, are also included in this section to allow direct comparison between experimental measurement and the theoretical prediction of suppression effectiveness, see section 6.4.

5.4.1. Suppressed Explosion Parameters

A typical suppressed explosion pressure/time record is sketched below:

![Diagram of suppressed explosion parameters](image-url)
The following suppressed explosion parameters were measured from the oscillograms:

- \( P_0 \) - initial pressure at ignition (gauge)
- \( P_A' \) - effective detection pressure (\( P_A = P_A' - P_0 \))
- \( P_{R*} \) - suppressed explosion pressure (gauge)
- \( P_R \) - suppressed explosion pressure including any influence of suppressant vapour pressure and suppressor propelling agent
- \( t_R, t_{R*} \) - time from detection to \( P_R \) or \( P_{R*} \)
- \( \frac{dP}{dt} \) - rate of pressure rise at detection.

For quiescent gas explosions \( P_0 = 0 \). Since the dust dispersion procedure produces an overpressure, \( P_0 \), prior to ignition, the effective detection pressure is \( P_A = P_A' - P_0 \). The distinction is made between \( P_R \) and \( P_{R*} \) since the latter occurs significantly later than the suppressor(s) discharge time(s) and reflects the influence of propelling agent pressure and suppressant vapour pressure on the measured overpressure in the vessel. The parameter, \( \frac{dP}{dt} \), provides an indication of the severity of the explosion that has been suppressed.

Figure 53 presents oscillograms of typical suppressed explosion events and identifies three types of suppression:

(i) TYPE \( S_1 \): very fast and effective suppression, \( P_R < P_{R*} \), maximum system overpressure is largely a consequence of propelling agent pressure and suppressant vapour pressure;
TYPE $S_2$: effective suppression, $P_R \geq P_R^*$, maximum system overpressure reflects the influence of the explosion;

TYPE $S_3$: less effective suppression, $P_R$ cannot be distinguished from $P_R^*$, maximum system overpressure occurs late largely as a consequence of the explosion severity.

In some experiments, the suppression system failed to arrest the developing explosion. Figure 54 presents oscillograms of typical failed suppression events and identifies two types of failed suppression:

(i) TYPE $F_1$: complete failure to suppress the developing explosion, $P_R$ cannot be distinguished from $P_R^*$, and $P_R$ and $P_R \geq P_{max}$;

(ii) TYPE $F_2$: 'just' failed to suppress the developing explosion, $P_R \ll P_{max}$ but $P_R^* \geq P_{max}$, the value of $P_R$ represents the pressure to which explosion was 'almost' suppressed.

5.4.2. Collaborative Experiments in 1m$^3$ Vessel

In these experiments a single exit (76mm diameter) HRD explosion suppressor mounted centrally on the top of the explosion vessel was used.

5.4.2.1. Datum Experiments

The following datum experiments provide information on the influence of the experimental procedure on the measured suppressed explosion pressures:
TEST A1: Fuel dust dispersion ($P_{AIR} = 2$ MPa)
No ignition
Measured overpressure - 12kPa

TEST A2: No dust dispersion
10kJ pyrotechnic igniter activated
Measured overpressure - 6kPa

TEST A3: Fuel dust dispersion ($P_{AIR} = 2$ MPa)
No ignition
Suppressor discharged (4kg powder, $P_{N_2} = 6$ MPa)
Measured overpressure - 28kPa

TEST A4: No dust dispersion
10kJ pyrotechnic igniter activated
Suppressor discharged (4kg powder, $P_{N_2} = 6$ MPa)
Measured overpressure 26kPa

5.4.2.2. Gas Explosions

The results of explosion suppression trials undertaken using the four suppressants: water, a mono-ammonium phosphate powder, Halon 1011 and Halon 1211 against quiescent 15 Vol % 70/30 CH$_4$/H$_2$ - air explosions are presented in Table 5.41.

The suppression effectiveness of 4kg of mono-ammonium phosphate based powder, and of 4kg of Halon 1011 against turbulent 9 Vol % CH$_4$ - air and 15 Vol % 70/30 CH$_4$/H$_2$ - air explosions was evaluated. The results of these trials are presented in Table 5.42.
<table>
<thead>
<tr>
<th>TEST NO</th>
<th>SUPPRESSANT</th>
<th>$P_A$ (kPa)</th>
<th>$P_{N_2}$ MPa</th>
<th>$(dP/dt)_{PA}$ MPa s$^{-1}$</th>
<th>$t_R$ ms</th>
<th>$P_R^*$ kPa</th>
<th>$P_A^*$ kPa</th>
<th>CURVE TYPE</th>
<th>COMPUTER ESTIMATE kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4kg Water</td>
<td>10</td>
<td>2</td>
<td>0.65</td>
<td>45</td>
<td>*</td>
<td>340</td>
<td>$S_3$</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
<td>2</td>
<td>4kg Water</td>
<td>10</td>
<td>4</td>
<td>0.67</td>
<td>90</td>
<td>*</td>
<td>300</td>
<td>$S_3$</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
<td>3</td>
<td>4kg Water</td>
<td>10</td>
<td>6</td>
<td>0.65</td>
<td>60</td>
<td>-</td>
<td>530</td>
<td>$S_3$</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
<td>4</td>
<td>4kg Powder</td>
<td>10</td>
<td>2</td>
<td>0.36</td>
<td>10</td>
<td>14</td>
<td>13</td>
<td>$S_2$</td>
<td>33</td>
</tr>
<tr>
<td>5</td>
<td>4kg Powder</td>
<td>10</td>
<td>4</td>
<td>0.63</td>
<td>8</td>
<td>19</td>
<td>26</td>
<td>$S_1$</td>
<td>28</td>
</tr>
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<td>4kg Powder</td>
<td>10</td>
<td>6</td>
<td>0.71</td>
<td>5</td>
<td>18</td>
<td>28</td>
<td>$S_1$</td>
<td>25</td>
</tr>
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<td>4kg Powder</td>
<td>30</td>
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<td>1.25</td>
<td>15</td>
<td>57</td>
<td>69</td>
<td>$S_1$</td>
<td>82</td>
</tr>
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<td>4kg Powder</td>
<td>30</td>
<td>4</td>
<td>1.37</td>
<td>10</td>
<td>52</td>
<td>53</td>
<td>$S_1$</td>
<td>70</td>
</tr>
<tr>
<td>9</td>
<td>4kg Powder</td>
<td>30</td>
<td>6</td>
<td>1.43</td>
<td>4</td>
<td>43</td>
<td>39</td>
<td>$S_2$</td>
<td>64</td>
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<td>4kg Powder</td>
<td>50</td>
<td>2</td>
<td>2.08</td>
<td>14</td>
<td>85</td>
<td>84</td>
<td>$S_2$</td>
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</tr>
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<td>50</td>
<td>4</td>
<td>1.68</td>
<td>9</td>
<td>70</td>
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<td>$S_2$</td>
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</tr>
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<td>70</td>
<td>55</td>
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</tr>
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<td>22</td>
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<td>22</td>
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</tr>
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<td>0.44</td>
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<td>23</td>
<td>$S_1$</td>
<td>27</td>
</tr>
<tr>
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<td>4kg Halon 1011</td>
<td>10</td>
<td>6</td>
<td>0.40</td>
<td>8</td>
<td>15</td>
<td>31</td>
<td>$S_1$</td>
<td>24</td>
</tr>
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<td>1.07</td>
<td>25</td>
<td>64</td>
<td>62</td>
<td>$S_2$</td>
<td>101</td>
</tr>
<tr>
<td>17</td>
<td>4kg Halon 1011</td>
<td>30</td>
<td>4</td>
<td>1.30</td>
<td>15</td>
<td>54</td>
<td>52</td>
<td>$S_2$</td>
<td>80</td>
</tr>
<tr>
<td>18</td>
<td>4kg Halon 1011</td>
<td>30</td>
<td>6</td>
<td>1.15</td>
<td>10</td>
<td>51</td>
<td>49</td>
<td>$S_2$</td>
<td>71</td>
</tr>
<tr>
<td>19</td>
<td>4kg Halon 1011</td>
<td>30</td>
<td>6</td>
<td>1.48</td>
<td>11</td>
<td>50</td>
<td>49</td>
<td>$S_2$</td>
<td>71</td>
</tr>
<tr>
<td>20</td>
<td>4kg Halon 1011</td>
<td>50</td>
<td>2</td>
<td>1.40</td>
<td>300</td>
<td>*</td>
<td>925</td>
<td>$F_2$</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
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<td>4kg Halon 1011</td>
<td>50</td>
<td>2</td>
<td>1.85</td>
<td>250</td>
<td>*</td>
<td>955</td>
<td>$F_1$</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
<td>22</td>
<td>4kg Halon 1011</td>
<td>50</td>
<td>4</td>
<td>1.85</td>
<td>75</td>
<td>*</td>
<td>126</td>
<td>$S_3$</td>
<td>139</td>
</tr>
<tr>
<td>23</td>
<td>4kg Halon 1011</td>
<td>50</td>
<td>6</td>
<td>1.47</td>
<td>19</td>
<td>84</td>
<td>85</td>
<td>$S_1$</td>
<td>124</td>
</tr>
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<td>24</td>
<td>4kg Halon 1011</td>
<td>5</td>
<td>2</td>
<td>0.56</td>
<td>20</td>
<td>20</td>
<td>18</td>
<td>$S_1$</td>
<td>23</td>
</tr>
<tr>
<td>25</td>
<td>2kg Halon 1011</td>
<td>5</td>
<td>2</td>
<td>0.42</td>
<td>14</td>
<td>12</td>
<td>17</td>
<td>$S_2$</td>
<td>23</td>
</tr>
<tr>
<td>26</td>
<td>1.5kg Halon 1011</td>
<td>5</td>
<td>2</td>
<td>0.50</td>
<td>8</td>
<td>*</td>
<td>18</td>
<td>$S_3$</td>
<td>23</td>
</tr>
<tr>
<td>27</td>
<td>3kg Powder</td>
<td>10</td>
<td>6</td>
<td>0.67</td>
<td>7</td>
<td>22</td>
<td>37</td>
<td>$S_1$</td>
<td>25</td>
</tr>
<tr>
<td>28</td>
<td>2kg Powder</td>
<td>10</td>
<td>6</td>
<td>0.67</td>
<td>7</td>
<td>*</td>
<td>42</td>
<td>$S_2$</td>
<td>25</td>
</tr>
<tr>
<td>29</td>
<td>4kg Halon 1211</td>
<td>10</td>
<td>2</td>
<td>1.50</td>
<td>35</td>
<td>56</td>
<td>120</td>
<td>$S_1$</td>
<td>140</td>
</tr>
</tbody>
</table>

* $t_R$ refers to $P_R^*$ rather than $P_R$.  

**TABLE 5.41.**
<table>
<thead>
<tr>
<th>TEST NO</th>
<th>FUEL</th>
<th>SUPPRESSANT</th>
<th>$t_v$</th>
<th>$P_o$</th>
<th>$P_A$</th>
<th>$t_R$</th>
<th>$P_R$</th>
<th>$P^*$</th>
<th>CURVE TYPE</th>
<th>COMPUTER ESTIMATE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>s</td>
<td>kPa</td>
<td>kPa</td>
<td>ms</td>
<td>kPa</td>
<td>kPa</td>
<td></td>
<td>kPa</td>
</tr>
<tr>
<td>30</td>
<td>9 Vol % CH$_4$</td>
<td>4kg Powder $P_{N_2} = 6$ MPa</td>
<td>0.3</td>
<td>11</td>
<td>10</td>
<td>30*</td>
<td>-</td>
<td>400</td>
<td>$S_3$</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
<td>31</td>
<td>9 Vol % CH$_4$</td>
<td>$P_{N_2} = 6$ MPa</td>
<td>0.6</td>
<td>12</td>
<td>9</td>
<td>9</td>
<td>46</td>
<td>48</td>
<td>$S_1$</td>
<td>100</td>
</tr>
<tr>
<td>32</td>
<td>CH$_4$</td>
<td>4kg Halon 1011 $P_{N_2} = 6$ MPa</td>
<td>0.3</td>
<td>11</td>
<td>9</td>
<td>500*</td>
<td>-</td>
<td>1160</td>
<td>$F_1$</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
<td>33</td>
<td>CH$_4$</td>
<td>4kg Halon 1011 $P_{N_2} = 6$ MPa</td>
<td>0.5</td>
<td>8</td>
<td>12</td>
<td>45</td>
<td>68</td>
<td>104</td>
<td>$S_2$</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
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<td>4kg Halon 1011 $P_{N_2} = 6$ MPa</td>
<td>0.6</td>
<td>13</td>
<td>7</td>
<td>18</td>
<td>56</td>
<td>60</td>
<td>$S_2$</td>
<td>115 PR</td>
</tr>
<tr>
<td>35</td>
<td>CH$_4$</td>
<td>4kg Powder $P_{N_2} = 6$ MPa</td>
<td>0.3</td>
<td>10</td>
<td>8</td>
<td>20*</td>
<td>-</td>
<td>510</td>
<td>$S_3$</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
<td>36</td>
<td>CH$_4$</td>
<td>4kg Powder $P_{N_2} = 6$ MPa</td>
<td>0.6</td>
<td>12</td>
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<td>12</td>
<td>53</td>
<td>52</td>
<td>$S_2$</td>
<td>180</td>
</tr>
<tr>
<td>37</td>
<td>CH$_4$</td>
<td>4kg Halon 1011 $P_{N_2} = 6$ MPa</td>
<td>0.9</td>
<td>11</td>
<td>9</td>
<td>10</td>
<td>46</td>
<td>45</td>
<td>$S_2$</td>
<td>64</td>
</tr>
<tr>
<td>38</td>
<td>CH$_4$/H$_2$</td>
<td>15 Vol % 70/30</td>
<td>1.5</td>
<td>13</td>
<td>11</td>
<td>10</td>
<td>48</td>
<td>46</td>
<td>$S_2$</td>
<td>39</td>
</tr>
<tr>
<td>39</td>
<td>CH$_4$/H$_2$</td>
<td>15 Vol % 70/30</td>
<td>0.3</td>
<td>11</td>
<td>14</td>
<td>180*</td>
<td>-</td>
<td>1230</td>
<td>$F_1$</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
<td>40</td>
<td>CH$_4$/H$_2$</td>
<td>15 Vol % 70/30</td>
<td>0.6</td>
<td>13</td>
<td>11</td>
<td>180*</td>
<td>-</td>
<td>1100</td>
<td>$F_1$</td>
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</tr>
<tr>
<td>41</td>
<td>CH$_4$/H$_2$</td>
<td>15 Vol % 70/30</td>
<td>0.9</td>
<td>13</td>
<td>7</td>
<td>13</td>
<td>40</td>
<td>47</td>
<td>$S_1$</td>
<td>71</td>
</tr>
<tr>
<td>42</td>
<td>CH$_4$/H$_2$</td>
<td>15 Vol % 70/30</td>
<td>1.5</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>52</td>
<td>52</td>
<td>$S_2$</td>
<td>149 PR</td>
</tr>
<tr>
<td>43</td>
<td>CH$_4$/H$_2$</td>
<td>15 Vol % 70/30</td>
<td>1.5</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>52</td>
<td>52</td>
<td>$S_2$</td>
<td>108</td>
</tr>
<tr>
<td>44</td>
<td>CH$_4$/H$_2$</td>
<td>15 Vol % 70/30</td>
<td>0.3</td>
<td>10</td>
<td>3</td>
<td>280*</td>
<td>-</td>
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**Table 5.42.**

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<th>$(dP/dt)_{PA}$</th>
<th>$P_o$</th>
<th>$t_R$</th>
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<th>CURVE TYPE</th>
<th>COMPUTER ESTIMATE</th>
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<td>MPa</td>
<td>MPa s$^{-1}$</td>
<td>kPa</td>
<td>ms</td>
<td>kPa</td>
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**Table 5.43.**

$t_r$ refers to $P^*$ rather than $P_R$

$P_R$ refers to a 'Poor Reliability' computer prediction of suppression effectiveness (see section 3.4.5.).
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<th>$P_o$</th>
<th>$t_R$</th>
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<td>56</td>
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<td>2</td>
<td>0.76</td>
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<td>240</td>
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<td>1090</td>
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<td>1090</td>
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</tr>
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</table>

* $t_R$ refers to $P_R^*$.

PR refers to a 'Poor Reliability' computer prediction of suppression effectiveness (see section 3.4.5.)

TABLE 5.44.
5.4.2.3. Dust Explosions

The results of explosion suppression trials undertaken using the four suppressants: water, a mono-ammonium phosphate powder, Halon 1011, and Halon 1211 against both bituminous coal dust \((0.25 \text{ kg m}^{-3})\) and cellulose dust \((0.75 \text{ kg m}^{-3})\) explosions in the \(1 \text{ m}^3\) vessel are summarised in Tables 5.43 and 5.44 respectively. These tests were undertaken with an ignition delay \(t_v = 0.6 \text{s}\).

5.4.3. Suppression Trials in the \(6.2 \text{m}^3\) IEP Test Apparatus

5.4.3.1. Datum Experiments

The following datum experiments provided information on the influence of experimental procedure on the measured suppressed explosion overpressure:

- TEST B1: Fuel dust dispersion \((P_{\text{AIR}} = 2 \text{ MPa})\)
  - No ignition
  - Measured overpressure \(6 \text{kPa}\)

- TEST B2: No dust dispersion
  - 100J spark ignition activated
  - Measured overpressure \(0.02 \text{kPa}\)

5.4.3.2. Gas Explosions

The results of explosion suppression trials undertaken using the three suppressants: water, a mono-ammonium phosphate powder, and Halon 1011 against quiescent 10 Vol % \(\text{CH}_4\) – air and quiescent 15 Vol % 70/30 \(\text{CH}_4/\text{H}_2\) – air explosions are presented in Table 5.45.
5.4.3.3. Dust Explosions

Explosion suppression trials were undertaken against turbulent cellulose dust (Batch WM2) in the 6.2 m$^3$ vessel using the three suppressants: water, mono-ammonium phosphate powder, and Halon 1011. The results of these trials are summarised in Table 5.46.
<table>
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<th>TEST NO</th>
<th>FUEL</th>
<th>SUPPN SYSTEM</th>
<th>P N₂</th>
<th>SUPPRESSANT</th>
<th>P_A (dP/dt)_PA</th>
<th>t_R</th>
<th>P_R</th>
<th>P_R*</th>
<th>CURVE TYPE</th>
<th>COMPUTER ESTIMATE</th>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>3</td>
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<td></td>
<td>46 0.72 31 58 42 S₁</td>
<td></td>
<td></td>
<td></td>
<td>66*</td>
<td></td>
</tr>
<tr>
<td>105</td>
<td></td>
<td></td>
<td></td>
<td>Halon 1011</td>
<td>17 0.32 204* - 830 F₁</td>
<td></td>
<td></td>
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<td>48</td>
<td></td>
</tr>
<tr>
<td>106</td>
<td></td>
<td></td>
<td></td>
<td>Water</td>
<td>12 0.20 112* - 620 F₁</td>
<td></td>
<td></td>
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<td>FAIL SUPPN</td>
<td></td>
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<tr>
<td>107</td>
<td>CH₄/</td>
<td>3 x 3dm³ HRDs</td>
<td>2</td>
<td>Halon 1011</td>
<td>8 0.24 20 26 - S₂</td>
<td></td>
<td></td>
<td></td>
<td>43</td>
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</table>

**TABLE 5.45.**

<table>
<thead>
<tr>
<th>TEST NO</th>
<th>t_v</th>
<th>SUPPN SYSTEM</th>
<th>P N₂</th>
<th>SUPPRESSANT</th>
<th>P_A (dP/dt)_PA</th>
<th>t_R</th>
<th>P_R</th>
<th>P_R*</th>
<th>CURVE TYPE</th>
<th>COMPUTER ESTIMATE</th>
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</thead>
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<tr>
<td>108</td>
<td>1 x 30 dm³ HRD</td>
<td>8</td>
<td>0.44 245* 4 - 600 F₁</td>
<td></td>
<td></td>
<td></td>
<td>19 0.91 250* 6 - 635 F₁</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>109</td>
<td>3 x 10 dm³ HRDs</td>
<td>5</td>
<td>0.32 30 6 29 28 S₂</td>
<td></td>
<td></td>
<td></td>
<td>16 0.74 38 5 74 - S₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>WATER</td>
<td>26 0.92 48 5 107 480 F₂</td>
<td></td>
<td></td>
<td></td>
<td>4 0.19 25 5 20 680 F₂</td>
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<td></td>
<td></td>
<td>486 PR</td>
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<tr>
<td>111</td>
<td>4 x 3 dm³ HRDs</td>
<td>4</td>
<td>0.30 2.5 4 8 - 12 S₁</td>
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<td></td>
<td></td>
<td>10 0.54 76* 5 49 49 S₁</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>112</td>
<td>3 x 4 dm³ HRDs</td>
<td>23 1.12 16 4 54 66 S₁</td>
<td></td>
<td></td>
<td></td>
<td>40 1.88 1/2 4 - 90 S₁</td>
<td></td>
<td></td>
<td></td>
<td>FAIL SUPPN</td>
</tr>
<tr>
<td>113</td>
<td>POWDER</td>
<td>63 2.76 310* 5 240 380 F₂</td>
<td></td>
<td></td>
<td></td>
<td>40 0.08 24 4 10 13 S₁</td>
<td></td>
<td></td>
<td></td>
<td>128</td>
</tr>
<tr>
<td>114</td>
<td>3 x 4 dm³ HRDs</td>
<td>4.5 0.20 650* 5 - 900 F₁</td>
<td></td>
<td></td>
<td></td>
<td>10 0.20 560* 6 - 1000 F₁</td>
<td></td>
<td></td>
<td></td>
<td>FAIL SUPPN</td>
</tr>
<tr>
<td>115</td>
<td>4 x 3 dm³ HRDs</td>
<td>3.5 0.10 1650* 4 16 895 F₂</td>
<td></td>
<td></td>
<td></td>
<td>3.5 0.08 24 4 10 13 S₁</td>
<td></td>
<td></td>
<td></td>
<td>45 PR</td>
</tr>
<tr>
<td>116</td>
<td>3 x 3 dm³ HRDs</td>
<td>3.5 0.15 51 6 17 14 S₁</td>
<td></td>
<td></td>
<td></td>
<td>3.5 0.15 51 6 17 14 S₂</td>
<td></td>
<td></td>
<td></td>
<td>41</td>
</tr>
</tbody>
</table>

**TABLE 5.46.**
PLATE XVI: Explosion Suppression System fitted to a Sugar Elevator
6. DISCUSSION

6.1. Explosions

The term 'explosion hazard' refers generally to both the risk of an explosion event, and the potential consequences of that explosion on personnel and the environment. When consideration is being given to the design of adequate explosion protection measures the explosion hazard is assessed in terms of the severest explosion that can occur with the given explosible material in the particular industrial environment.

At the beginning of this research programme, the unequivocal determination of the explosibility parameters of quiescent flammable gas-air mixtures was established, and it was recognised that turbulence resulted in more violent explosions. Turbulence was defined and quantified empirically. For the measurement of the explosibility parameters of combustible dusts there existed a plurality of test apparatus and test methods which gave widely differing data for a given dust. Explosion hazard assessment based on a Hartmann apparatus determination of dust explosibility was considered suspect, which was of great concern since this test was the accepted standard in the UK and USA. The work on explosion hazard assessment described in this thesis has been directed at appraising the validity of established test procedures. It has sought also to identify the reasons for the measured differences in explosion parameters obtained using different apparatus, and thus to establish a sounder foundation for more meaningful test procedures.

The rate of explosion propagation is influenced by the dispersed fuel concentration, homogeneity, and turbulence, and also by the vessel geometry and the nature and the location of the ignition source. Particulate materials have additional factors influencing their explosibility; these include purity,
particle size distribution, surface topography and moisture content. The complexity of the situation demands that a representative sample of the material must be tested to determine its explosion characteristics.

6.1.1. Quiescent Gas Explosions

Published data, see section 2.2., have established that explosibility measurements of quiescent gas/air mixtures can be scaled by the cube law:

\[
\left( \frac{dP}{dt} \right)_{\text{max}} \cdot V^\frac{3}{5} = K \quad \text{(explosion rate constant)}
\]

This has been proved by measurements in test volumes ranging from 1dm³ to 20m³. Literature data pertinent to the flammable gases studied in this research are summarised in Table 6.1. below:

<table>
<thead>
<tr>
<th>GAS</th>
<th>CONCENTRATION Vol %</th>
<th>P max MPa</th>
<th>K MPa m⁻¹</th>
<th>S u m⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>9.5</td>
<td>0.75</td>
<td>5.4</td>
<td>0.33</td>
</tr>
<tr>
<td>70/30 CH₄/H₂</td>
<td>15</td>
<td>0.70</td>
<td>8.6</td>
<td>-</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>4</td>
<td>0.70</td>
<td>7.3</td>
<td>0.46</td>
</tr>
</tbody>
</table>

**TABLE 6.1.**

Results of quiescent gas explosion experiments undertaken in the five test apparatus are presented in section 5.1., and the pertinent explosibility determinations are collated in Table 6.2 below:
<table>
<thead>
<tr>
<th>GAS</th>
<th>TEST APPARATUS</th>
<th>CONCENTRATION</th>
<th>Vol %</th>
<th>$P_{\text{max}}$</th>
<th>$K$</th>
<th>$S_u$</th>
<th>$S_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>1.23dm$^3$ Hartmann Tube</td>
<td></td>
<td>9.5</td>
<td>0.60</td>
<td>2.95</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.75dm$^3$ 1:1 AR Tube</td>
<td></td>
<td>9.5</td>
<td>0.69</td>
<td>6.04</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>43dm$^3$ Sphere</td>
<td></td>
<td>10.5</td>
<td>0.69</td>
<td>6.16</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1m$^3$ Cylinder</td>
<td></td>
<td>9.0</td>
<td>0.74</td>
<td>5.80</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.2m$^3$ Cylinder</td>
<td></td>
<td>10.2</td>
<td>0.72</td>
<td>5.69</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.75dm$^3$ 1:1 AR Tube</td>
<td>14.5</td>
<td>0.74</td>
<td>8.95</td>
<td>0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>43dm$^3$ Sphere</td>
<td>14.0</td>
<td>0.69</td>
<td>8.98</td>
<td>0.45</td>
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<td></td>
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<tr>
<td></td>
<td>1m$^3$ Cylinder</td>
<td>15.0</td>
<td>0.72</td>
<td>9.50</td>
<td>0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.2m$^3$ Cylinder*</td>
<td>15.0</td>
<td>0.78</td>
<td>9.54</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70/30 CH$_4$/H$_2$</td>
<td>43dm$^3$ Sphere</td>
<td>4.5</td>
<td>0.80</td>
<td>11.9</td>
<td>0.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.2m$^3$ Cylinder</td>
<td>4.0</td>
<td>0.78</td>
<td>9.2</td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.2m$^3$ Cylinder*</td>
<td>5.2</td>
<td>0.86</td>
<td>36.4</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Anomalously high $K$ values were recorded at specific fuel gas concentrations.

**TABLE 6.2.**

The correspondence between $S_u$ values determined in the five test volumes, ranging from 1.23dm$^3$ to 6.2m$^3$, was very good and in general agreement with the published values. With the exception of Hartmann apparatus data, the measured explosibility rate constants of CH$_4$ and 70/30 CH$_4$/H$_2$ flammable gases were essentially invariant over the range of test volumes and also conformed with published values. Anomalous explosion results were obtained in the 6.2m$^3$ vessel, particularly with C$_3$H$_8$-air mixtures, and are discussed in some detail later in this section.
The Hartmann apparatus underestimated the explosion violence of quiescent CH$_4$/air mixtures. It can be deduced from the shape of the corresponding pressure/time records, see Figure 18, that the expanding fireball is partially quenched, firstly at the combustion tube walls, and then at the base of explosion tube; the ignition electrodes are located 0.13m from the bottom of the 0.3m long explosion tube. Premature wall quenching does not occur in near 1:1 aspect ratio vessels and the explosibility rate constant, K, was reasonably well defined in such vessels over the large range of volumes used. Calculation of $S_u$ from the early part of explosion pressure/time records obtained using the Hartmann apparatus provided meaningful data in agreement with data obtained using other test vessels and thus supported the hypothesis that fully developed quiescent gas explosions are quenched prematurely by the vessel walls in the Hartmann tube.

The influence of the spark ignition energy on the course of quiescent gas explosion development was studied in the 43dm$^3$ spherical apparatus, see section 5.1.4.1. Table 5.14 identifies an apparent inverse correlation between $(dP/dt)_{\text{max}}$ measurements and the spark ignition energy. It was evident from a study of the explosion pressure/time records, see Figure 32, that an increment in igniting spark energy has the effect of truncating the early part of the pressure/time event. However, for any defined pressure $P < \frac{1}{2}P_{\text{max}}$, the measured rate of pressure rise $(dP/dt)_p$ was independent of the igniting spark energy. It was observed further that $(dP/dt)_{\text{max}}$ occurred at a lower explosion pressure when the explosion was ignited by a high energy spark and had a consequently lower value; this effect is not fully understood. One explanation is that the ignition electrodes were not exactly centrally located, and that ignition with a low energy spark provided more time for the developing fireball to 'centralise' as pressure equalised either side of the combustion wave in the early stages of explosion development.
Thus, wall quenching occurred at an increased fireball radius (higher pressure) compared to high energy spark ignition. This study has indicated that ignition energy can influence the measured explosion parameters of quiescent gas explosions, but that the course of explosion pressure development is essentially invariant provided that the ignition energy is small relative to the final maximum explosion energy.

Quiescent gas explosions in the 6.2 m$^3$ vessel provided some interesting and unexpected results, see section 5.1.5. The pressure/time records of CH$_4$/air explosions exhibited a 'doublet' which was more distinct at specific CH$_4$ concentrations. The explosion pressure increased predictably to $\approx 0.4$ MPa, and then rose more sharply to the maximum pressure. This second pressure rise was accompanied by spurious pressure oscillations. The effect was evident with both induction coil spark (30 mJ) and capacitive spark (100 J) ignition. The pressure/time records of 70/30 CH$_4$/H$_2$ - air explosions exhibited a similar but more pronounced 'doublet' at specific concentrations below and above stoichiometry. The perturbation on the pressure/time records occurred at 0.2 - 0.3 MPa and the subsequent pressure changes were usually oscillatory. C$_3$H$_8$/air explosions in the 6.2 m$^3$ vessel demonstrated a distinct and very pronounced transition at ($P_r$, $t_r$) for all fuel gas concentrations $\geq 4.5$ Vol %. Violent oscillations on the pressure/time records occurred at $t > t_r$. The observations from quiescent gas explosion trials in the 6.2 m$^3$ vessel are summarised below:

(i) CH$_4$/air explosion data, see Figure 37, ignoring the artefact of the observed 'doublet' late in the explosion, are in agreement with published data;
(ii) 70/30 CH\textsubscript{4}/H\textsubscript{2} - air explosion data, see Figure 38, identify two explosion types. The occurrence of a 'doublet' at specific fuel gas concentrations masks meaningful (dP/dt)\textsubscript{max} measurement. The calculated S\textsubscript{u} values from the early part of the P/t records are all self-consistent. The maximum K value occurs at a different fuel gas concentration to that corresponding to the maximum S\textsubscript{u} value. A (dP/dt)\textsubscript{max} value of 5.2 MPa s\textsuperscript{-1} at the stoichiometric concentration is consistent with the reported value for this gas.

(iii) C\textsubscript{3}H\textsubscript{8} - air explosion data, see Figure 39, identify two distinct regimes. At fuel rich concentrations a distinct transition always occurred. The calculated S\textsubscript{u} values from the pre-transition regime of the P/t records are all self consistent. The maximum K value occurs at a different fuel gas concentration to that corresponding to the maximum S\textsubscript{u} value. The maximum (dP/dt)\textsubscript{max} measurement of 19.8 MPa s\textsuperscript{-1} at \( \sim 5 \) Vol \% C\textsubscript{3}H\textsubscript{8} is very significantly higher than the literature value of \( \sim 4 \) MPa s\textsuperscript{-1} at the stoichiometric concentration of 4 Vol \% C\textsubscript{3}H\textsubscript{8}.

The 'doublet' type pressure/time explosion records identified in the 6.2m\textsuperscript{3} trials have been reported with C\textsubscript{3}H\textsubscript{8} - air mixtures ignited at elevated pressures (108), and very recently by Bartknecht (245) in 20dm\textsuperscript{3} and 30dm\textsuperscript{3} spherical apparatus, but only using high energy spark ignition. These effects are not reported with CH\textsubscript{4} or 70/30 CH\textsubscript{4}/H\textsubscript{2} flammable gas-air mixtures and were not observed in corresponding 43dm\textsuperscript{3} and 1m\textsuperscript{3} trials, which formed part of this research study. Table 5.28 shows that C\textsubscript{3}H\textsubscript{8} - air explosions exhibited a pronounced transition at \((P_{\gamma}, t_{\gamma})\) for all
concentrations greater than 4.5 Vol% in the 6.2 m³ vessel. \( P_\gamma \) decreased to a minimum value of \( \sim 0.014 \) MPa with increasing propane concentration, and \( t_\gamma \) increased with concentration increments. At a propane concentration of 6.6 Vol% the pre-transition time, \( t_\gamma \), exceeded 3 s, and yet the post-transition rate of pressure rise was greater than that reported in the literature for stoichiometric \( C_3H_8 \)-air mixtures.

The artefacts reported in the 6.2 m³ gas explosion trials are not fully understood. Figure 40 shows that the fireball growth in this 6.2 m³ vessel starts as a sphere, and subsequently grows as a buoyant ellipsoid. It is evident that the observed perturbation on the pressure/time record occurs when the fireball is in very close proximity to the vessel walls. Strain gauge measurements have indicated very violent axial shock loadings when a 'doublet' or 'transition' results.

It is tempting to suggest that the 'doublet' type pressure/time record is a consequence of premature wall quenching in this larger aspect ratio vessel, akin to that identified with quiescent gas explosions in the Hartmann tube. However, the observed higher rate of pressure rise cannot be explained by this mechanism alone. Perhaps induced turbulence results in the break up of the laminar diffusion controlled combustion wave when it reaches the vessel wall, thus resulting in subsequent more violent combustion. The observed oscillations may reflect a sonic resonance of the explosion chamber initiated by the explosion shock wave. The oscillations had a periodicity of 160 Hz and in the more violent transitions there was a superimposed 450 Hz component which dominated this 160 Hz fundamental oscillation. These frequencies were constant, irrespective of flammable gas or explosion violence.
The above postulates would be expected to occur at all fuel gas concentrations, or at least at specific regimes of flame speed or explosion violence. This was not observed, thus suggesting that the artefacts are a consequence of some chemical influence during the course of the explosion development. One hypothesis is that the effect may be the consequence of some autoignition, akin to the mechanism of 'knocking' observed in combustion engines. 'Knocking' and autoignition are known to be related to cool flame phenomena, which, in turn, are controlled by chemical processes of hydrocarbon oxidation. It is significant that propane is the lowest molecular weight alkane to exhibit cool flames. It is mechanistically impossible for methane to show this effect (4), although methane can autoignite at elevated temperature and pressures. For C₃H₈/air mixtures cool flames occur typically at 0.12 - 0.15 MPa at 300°C (246), and this accords well with the observed limiting Pₒ value identified in Table 5.28. There is usually a delay before the onset of cool flames. In smaller vessels, the explosion duration is shorter and hence cool flames would be less likely. Higher alkanes would exhibit the same transition effect if the cool flame hypothesis is correct. The observed transition with C₃H₈/air mixtures may be attributable to cool flame phenomena, but the 'doublet' type artefacts observed with CH₄ and 70/30 CH₄/H₂ gases are not. Adiabatic heating, alone is insufficient to cause autoignition of CH₄/air mixtures, but a combination of adiabatic heating and radiant heating can be used to invoke heterogeneous ignition of the unburned explosive gases at the explosion chamber walls. The oscillatory nature of the pressure/time records are similar to those reported in compression ignition experiments (4), and therefore are characteristic of autoignition phenomena.

An alternative and more probable explanation of the reported artefacts is that the laminar deflagration is perturbed by reflected shock waves from the dished ends of the explosion chamber. Markstein (247) has shown that when a shock wave meets a combustion wave a rarefaction wave propagates backward into the unburned gas, and a jet of unburned gas develops which
penetrates deeply into the burned gas. The sudden increase in turbulence that results causes a large increase in the burning rate and the formation of trains of compression waves. The acceleration of the overall burning rate is enhanced by precompression and preheating of the unburned gas ahead of the combustion wave. Thus transient, non-steady state detonations are invoked under conditions which do not normally result in fully developed spherical detonations. The occurrence of such effects will be dependent on the vessel shape, and the chemistry of oxidation of the combustion fuel.

These 6.2m$^3$ quiescent gas explosion results were appraised by van Wigerden (248). In further investigations he identified such transitions with higher molecular weight hydrocarbon fuels and suggests that the transition is, indeed, a consequence of acoustic coupling of shock waves with the combustion wave. Van Wigerden postulates that such artefacts will be more prevalent with non-central ignition.

A detailed investigation into the above hypotheses was outside of the scope of this study. The data in Table 6.2 demonstrates that the calculated burning velocity, $S_u$, determined in any test apparatus provides an unambiguous measure of the explosion severity for the early stages of a quiescent gas explosion. Figure 40 demonstrates the good correspondence between theoretical and experimental pressure and fireball growth characteristics for the early part of quiescent gas explosions in a large vessel. Figures 37 - 39 define the most explosible concentrations of these fuels, based on $S_u$ data. It is probable that explosions of these fuel concentrations would be more difficult to suppress than explosions of fuel concentrations that result in anomalously high $(dP/dt)_{max}$ values, because the former provide the severest rate of pressure rise in the early stages of explosion pressure development.
6.1.2. Turbulent Gas Explosions

No attempt has been made to define the mechanisms of turbulent flame propagation, but the aim has been to quantify the influence of turbulence inasmuch as it affects explosion severity. Turbulent gas explosion data determined in the various test apparatus using ignition delays which correspond to those used for 'standard' dust explosibility measurements are collated in Table 6.3.

<table>
<thead>
<tr>
<th>GAS</th>
<th>TEST APPARATUS</th>
<th>t_v</th>
<th>P_o</th>
<th>P_max</th>
<th>K</th>
<th>Tu</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5 Vol %</td>
<td>1.23dm³ Hartmann Tube</td>
<td>100</td>
<td>42</td>
<td>0.86</td>
<td>6.8</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>1.75dm³ 1:1 AR Tube</td>
<td>100</td>
<td>31</td>
<td>0.87</td>
<td>19.6</td>
<td>2.7</td>
</tr>
<tr>
<td>CH₄</td>
<td>43dm³ Sphere</td>
<td>265</td>
<td>39</td>
<td>0.93</td>
<td>43.0</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>1m³ Cylinder</td>
<td>600</td>
<td>14</td>
<td>0.88</td>
<td>28.2</td>
<td>4.3</td>
</tr>
<tr>
<td>14.5 Vol %</td>
<td>1.75dm³ 1:1 AR Tube</td>
<td>100</td>
<td>28</td>
<td>0.85</td>
<td>27.6</td>
<td>2.8</td>
</tr>
<tr>
<td>70/30 CH₄/H₂</td>
<td>43dm³ Sphere</td>
<td>265</td>
<td>39</td>
<td>0.86</td>
<td>50.0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>1m³ Cylinder</td>
<td>600</td>
<td>15</td>
<td>0.88</td>
<td>41.9</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**TABLE 6.3.**

Turbulent gas explosions were ~3 - 5 times more violent than the corresponding quiescent gas explosions. With the implicit assumption*, see section 6.1.3., that the influence of turbulence is similar for both gases and dusts certain observations can be inferred from the data of Table 6.3:

(i) the turbulence level attained in the Hartmann tube is ~40% of that attained in the 1m³ apparatus; thus dust explosibility results obtained in the two apparatus may be expected to differ by a factor of ~2.5;

* see section 6.1.3.
(ii) The turbulence level attained in the 1.75dm^3 :1:1 aspect ratio tube is \( \sim 70\% \) of that attained in the 1m^3 apparatus, thus dust explosibility results obtained in the two apparatus may be expected to differ by a factor of \( \sim 1.5 \);

(iii) The turbulence level attained in the 43dm^3 apparatus is \( \sim 110\% \) of that attained in the 1m^3 apparatus, thus dust explosibility results obtained in the two apparatus may be expected to differ by a factor of \( \sim 1.1 \).

The pressure/time records of turbulent gas explosions in the Hartmann tube did not exhibit the fine structure identified with quiescent gas explosions. Results of turbulent 9.5 Vol \% CH\(_4\)/air explosions in both the Hartmann apparatus and the 1:1 aspect ratio vertical tube apparatus are presented graphically in Figure 55. Explosion intensity increased with increasing turbulence (reducing \( t_v \)). The disparity between \( K \) determinations in the two laboratory explosion test apparatus reflects the influence of the significant wall quenching that occurs in the standard Hartmann tube.

Tables 5.2 and 5.15 demonstrate a general correspondence between the two measures of turbulence factor, \( \alpha \) and \( T_u \), as defined in section 3.1.2. Figure 56 shows that \( (dP/dt)_{\text{max}} \) and \( \alpha \) are linearly related (\( \alpha \gg 1 \) ) with a slope which corresponds to the \( (dP/dt)_{\text{max}} \) value of the quiescent gas explosion. This supports the contention that \( \alpha \approx T_u \) and that turbulent gas explosibility data can be scaled from one test volume to another using the revised cube law derived in section 3.1.3.

\[
\left( \frac{dP}{dt} \right)_{\text{max}} \cdot \frac{V^\frac{1}{3}}{1} = \left( \frac{dP}{dt} \right)_{\text{max}} \cdot \frac{V^\frac{1}{3}}{2} \cdot \frac{1}{\alpha} \quad (25)
\]
Experimental plots of $\chi$ and Tu against the reciprocal ignition delay, $t_v^{-1}$, are presented in Figure 57. An increment in the 'absolute' turbulence level, $t_v^{-1}$, has a greater effect on the 'implied' turbulence level, $\chi$ or Tu, with CH$_4$ explosions, compared to 70/30 CH$_4$/H$_2$ explosions. This is consistent with the postulate (see section 3.1.2) that:

$$\chi S_u = S_u + S_g \quad (\chi \geq 1)$$

Hence $S_g$, the average air perturbation velocity resulting from the induced turbulence, is defined as:

$$S_g = (\chi - 1) S_u \quad (\chi \geq 1)$$

The relations between $S_g$ and $t_v$ for turbulent CH$_4$/air and 70/30 CH$_4$/H$_2$-air explosions in three test apparatus are presented graphically in Figure 58. The results for both fuel gases fit on the same curves. Hence these curves are, in effect, calibration curves for the particular test apparatus. Published turbulent gas explosibility data obtained from a standard test in a 54dm$^3$ apparatus (108) provided further support for the validity of equation (18). Calculation of $S_g$ from these data gave a 'constant' value for four fuels with very markedly different $K$ and Tu values, see Table 6.4.

<table>
<thead>
<tr>
<th>GAS</th>
<th>K</th>
<th>Tu</th>
<th>$S_u$</th>
<th>$S_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa m s$^{-1}$</td>
<td>m s$^{-1}$</td>
<td>m s$^{-1}$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>39</td>
<td>7.0</td>
<td>0.33</td>
<td>1.98</td>
</tr>
<tr>
<td>C$_3$H$_8$</td>
<td>51</td>
<td>5.6</td>
<td>0.45</td>
<td>2.07</td>
</tr>
<tr>
<td>Coal Gas</td>
<td>48</td>
<td>3.4</td>
<td>0.90</td>
<td>2.13</td>
</tr>
<tr>
<td>H$_2$</td>
<td>80</td>
<td>1.6</td>
<td>3.40</td>
<td>2.04</td>
</tr>
</tbody>
</table>

**TABLE 6.4.**

The results of this study have established a foundation for the empirical interpretation of turbulence derived in section 3.1.
6.1.3. Dust Explosions

Meaningful dust explosion hazard assessment is difficult. The first stage, however, requires a meaningful measurement of the 'absolute' explosibility of the dusts used in industrial processes. The experimental work on dust explosions reported in section 5.1. was undertaken to:

(i) seek to resolve the uncertainty associated with a Hartmann apparatus dust explosibility determination;

(ii) develop an alternative small scale explosion test apparatus for quantification of the explosibility of industrial dusts;

(iii) appraise the relative importance of turbulence on dust explosion severity and its implications to explosion hazard assessment;

(iv) determine an experimental procedure suitable for meaningful dust explosion trials in the 6.2m$^3$ IEP test facility.

6.1.3.1. Hartmann Apparatus - An Appraisal

Eckhoff (100) had shown previously that the measured explosion severity of lycopodium dust was sensitive to changes in the ignition delay time in the Hartmann apparatus. The influence of the Hartmann test procedure on the resultant explosibility measurement of a dust was evaluated using cellulose dust as a typical fuel. The chosen ignition source was the standard Rühmkoff coil spark generator, which was activated after a preset ignition delay $t^*$. It was noted, see Table 5.7., that effective ignition was not always achieved with the first spark, and that a significant time delay between activation of the Rühmkoff coil and actual ignition could result. The observed relation
between the preset ignition delay, $t'_v$, and the actual ignition delay, $t_v$, is presented in Figure 59. It is evident that for all values of $t'_v < 100\text{ms}$, the actual ignition delay $t_v$ was $\sim 100\text{ms}$. Figure 21 demonstrates the very strong influence of the ignition delay on the measured explosion parameters; $(dP/dt)_{\text{max}}$ decreases with increasing $t_v$. Since high speed ciné photography of the Hartmann apparatus dust dispersion procedure had shown that an explosible cellulose dust cloud surrounds the ignition source after only 60ms, it was surprising to find that ignition was not achieved with induction coil sparks for $60 < t_v < 100\text{ms}$. Effective ignition delay was achieved for all $t_v > 65\text{ms}$ with both 100J capacitive spark and fuse head ignition procedures. It was inferred therefore that ignition delay of cellulose dust is possible under more turbulent conditions when a higher energy ignition procedure is used.

The standard Hartmann hot coil ignition methodology usually results in higher $(dP/dt)_{\text{max}}$ values than are measured using the standard induction coil spark ignition methodology for industrial dusts. It is possible that this occurs because the dust cloud is ignited in a more homogeneous and turbulent condition with the hot coil ignition procedure, and thus with a shorter ignition delay. Comparative cellulose dust explosibility measurements in the Hartmann tube obtained using the hot coil, induction coil sparks, and 100J capacitor spark ignition procedures support this reasoning, see Table 5.7. At specific ignition delays, the explosion parameters are very similar, irrespective of the choice of ignition source. Thus a dust explosibility measurement in the Hartmann tube is sensitive to the ignition energy and ignition methodology only inasmuch as that affects the resultant ignition delay.

* There is a second order influence of ignition energy on the resultant $(dP/dt)_{\text{max}}$ measurement, see section 6.1.3.2.
In view of the above observations, experimental dust explosibility records of Hartmann tests, undertaken for industry over several years by Graviner Ltd., were re-examined. The ignition delay was estimated from the pressure/time record of the most explosible concentration of each dust tested using the standard hot coil ignition procedure. Figure 60 is a scatter diagram of the measured \( (dP/dt)_{\text{max}} \) values of over one hundred dusts, plotted against their corresponding ignition delay times. Extended ignition delays are in evidence for a significant number of the dusts, and it is probable that the reported explosibility of at least some of these dusts represent a gross underestimate of the potential explosion intensity of these samples. The correspondence between this analysis and Bartknecht's comparison of Hartmann and 1 m\(^3\) dust explosibility data (25) is evident, see Figures 60 and 61.

Comparative dust explosion tests in the Hartmann tube using either the 'sustained' hot coil or the 'discrete' 100J capacitive spark ignition procedures provide further evidence of the influence of test procedure on an explosibility measurement, see Table 5.8. These results, presented graphically in Figure 24, demonstrate a correspondence between the ratio of the \( (dP/dt)_{\text{max}} \) measurements, \( \xi \), and the observed ignition delay with the 'sustained' hot coil ignition procedure. As a generalisation less exploisible dusts are more likely to exhibit longer ignition delays in the standard Hartmann test and, hence, be ignited in conditions of lower turbulence.

This appraisal of the Hartmann test procedure has shown that the use of 'sustained' rather than 'discrete' ignition sources does not provide an unequivocal assessment of the explosibility of industrial dusts. The dispersed dust cloud homogeneity and turbulence are not constant for each dust because the ignition delay is not constant. In consequence, dusts which are
insensitive to ignition will exhibit longer ignition delays and therefore explode when the dust cloud is less turbulent. The use of an alternative test methodology with a 100J spark discrete ignition procedure removes largely the ambiguity, although such a procedure will not ignite all potentially explosive dust samples.

6.1.3.2. Development of the 43dm³ Apparatus

A 43dm³ explosion test apparatus was developed as a possible alternative to the Hartmann apparatus. Initially, the intention was to construct a larger volume Hartmann type apparatus using pneumatic dust dispersion and a sustained ignition source. It was found that dust dispersion via a pepper pot spreader, coupled with Rühmkoff coil spark ignition, resulted in excessive ignition delays and explosions of low intensity, see Table 5.16. The dust cloud produced with the pepper pot dust dispersion procedure could not be ignited with 100J capacitive spark for all $t < 200\text{ms}$, see Table 5.17, although high speed cine photography had shown that all of the dust sample was dispersed into the explosion chamber in less than 200ms. Ignition of the dust cloud was unreliable for $200 < t < 400\text{ms}$. The measured $(dP/dt)_{\text{max}}$ of cellulose dust decreased with increasing ignition delay, see Figure 34, reflecting the decrease of turbulence with time which is the characteristic of pneumatic dust dispersion procedures. Experiments using a range of capacitive spark ignition energies indicated that the probability of ignition increased with the higher spark ignition energies, see Table 5.18. Marginally higher $(dP/dt)_{\text{max}}$ values were obtained with the higher spark ignition energies. Corresponding pressure/time records are presented in Figure 62a and Figure 62b shows the theoretical relationship between explosion pressure and fireball radius for the 43dm³ apparatus. It is evident that propagation of the explosion away from the ignition kernel is delayed
with the lower ignition energies probably reflecting the differing spatial magnitudes of the kernel. Note that a significant overpressure (∼50kPa) does not result until the fireball has attained a radius of ∼150mm. This delay accounts for the lower \( (dP/dt)_{\text{max}} \) values since the dust cloud turbulence is decreasing as the fireball propagates away from the ignition kernel. Increasing the dust dispersion pressure resulted in increased \( (dP/dt)_{\text{max}} \) values because of the increased induced turbulence, see Table 5.19.

There were three reasons which may have contributed to unreliable ignition with the pepper pot dispersion methodology:

(i) explosible dust concentrations were not consistently achieved in the vicinity of the small spark kernel;

(ii) the velocity of the dust/air suspension across the ignition electrodes could exceed the flame speed, hence the residence time of the dust particulates in the ignition kernel was too short to attain sustained combustion;

(iii) the ignition kernel was quenched by the dust/air flow, thus preventing ignition.

In view of these experimental difficulties an alternative dust dispersion methodology using a spray ring was established and evaluated.

High speed cine photography showed that the dust sample was effectively dispersed into the 43dm\(^3\) explosion chamber through the spray ring in 210ms. Effective ignition was achieved with this dust dispersion procedure for all \( t > 90\text{ms} \) using a 100J capacitive spark, see Table 5.20. Figure 35 shows
the predictable decrease in both $S_u$ and $(dP/dt)_{\text{max}}$ with increasing ignition delay. Note that the most intense explosion occurred at $t_v = 170\text{ms}$, although measurements at $t_v < 210\text{ms}$ do not relate to a readily definable dust concentration because dust injection into the explosion chamber is still in progress. For $t_v < 210\text{ms}$, the most explosible dust concentration is not attained at ignition. However, increased $(dP/dt)_{\text{max}}$ measurements are observed for $170\text{ms} < t_v < 210\text{ms}$ because the higher turbulence outweighs the effect of the departure from the most explosible dust concentration.

Comparable cellulose dust explosibility data recorded in the $43\text{dm}^3$ apparatus using both pepper pot and spray ring dust dispersion procedures are summarised in Table 6.5.

<table>
<thead>
<tr>
<th>DUST DISPERSION PROCEDURE</th>
<th>IGNITION SOURCE</th>
<th>$t'_{\text{v}}$</th>
<th>$t_v$</th>
<th>$P_0$</th>
<th>$P_{\text{max}}$</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Pepper Pot' Spreader</td>
<td>Induction Sparks</td>
<td>0</td>
<td>285</td>
<td>28</td>
<td>0.93</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>100J Capacitive Spark</td>
<td>250</td>
<td>250</td>
<td>28</td>
<td>0.95</td>
<td>9.6</td>
</tr>
<tr>
<td>Spray Ring</td>
<td>Induction Sparks</td>
<td>0</td>
<td>460</td>
<td>28</td>
<td>0.96</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>100J Capacitive Sparks</td>
<td>265</td>
<td>265</td>
<td>28</td>
<td>0.98</td>
<td>12.8</td>
</tr>
</tbody>
</table>

**TABLE 6.5.**

Induction coil spark ignition results in a less intense explosion in this test apparatus because the effective ignition delay is long and the fireball is slow to propagate away from the ignition kernel. Note that, at $t_v = 210\text{ms}$ and using spray ring dispersion, the recorded explosibility of cellulose dust in
the 43dm$^3$ apparatus is comensurate with the maximum K results obtained in the 1m$^3$ apparatus, compare Tables 5.3. and 6.5. The average K measurement in the 1m$^3$ apparatus was 12.8 MPa, see section 5.1.1.2., thus $t_v = 265$ms results in comparable 43dm$^3$ data.

Both pepper pot and spray ring dust dispersion procedures produced an overpressure of \( \sim 28 \) kPa at ignition, which is comparable with that produced in the Hartmann apparatus. The 1m$^3$ apparatus dust dispersion procedure produced an overpressure of \( \sim 14 \) kPa. These overpressures, and the turbulence induced by the choice of dust dispersion pressure influence the explosibility measurement of dusts. Table 5.21. indicates the influence of these parameters on explosibility measurements in the 43dm$^3$ apparatus, and highlights the importance of using controlled experimental conditions for dust explosibility measurements.

It has been shown that, by the correct choice of experimental conditions, a small scale explosion test apparatus is capable of providing explosibility data comparable with that obtained in the 1m$^3$ apparatus.

6.1.3.3. Comparison of Test Apparatus

Cellulose dust explosibility results determined in the five test apparatus evaluated in this study are summarised in Table 6.6.
<table>
<thead>
<tr>
<th>TEST APPARATUS</th>
<th>IGNITION SOURCE</th>
<th>$t_v$</th>
<th>$t_v$</th>
<th>$P_0$</th>
<th>$P_{max}$</th>
<th>K</th>
<th>$\alpha S_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.23dm$^3$ Hartmann Tube</td>
<td>Hot Coil</td>
<td>0</td>
<td>80</td>
<td>28</td>
<td>0.77</td>
<td>3.6</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Induction Sparks</td>
<td>0</td>
<td>100</td>
<td>30</td>
<td>0.79</td>
<td>3.1</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>100J Capacitive Spark</td>
<td>100</td>
<td>100</td>
<td>30</td>
<td>0.78</td>
<td>3.4</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>100J Capacitive Spark</td>
<td>70</td>
<td>70</td>
<td>28</td>
<td>0.77</td>
<td>4.1</td>
<td>0.24</td>
</tr>
<tr>
<td>1.75dm$^3$ 1:1 Aspect Ratio Tube</td>
<td>Induction Sparks</td>
<td>0</td>
<td>100</td>
<td>25</td>
<td>0.77</td>
<td>3.4</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>100J Capacitive Spark</td>
<td>100</td>
<td>100</td>
<td>25</td>
<td>0.83</td>
<td>4.7</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>100J Capacitive Spark</td>
<td>70</td>
<td>70</td>
<td>20</td>
<td>0.83</td>
<td>6.3</td>
<td>0.33</td>
</tr>
<tr>
<td>43dm$^3$ Sphere (Spray Ring Dispersion)</td>
<td>Induction Sparks</td>
<td>9</td>
<td>460</td>
<td>28</td>
<td>0.96</td>
<td>5.9</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>10CJ Capacitive Spark</td>
<td>265</td>
<td>265</td>
<td>28</td>
<td>0.98</td>
<td>12.8</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>100J Capacitive Spark</td>
<td>210</td>
<td>210</td>
<td>28</td>
<td>0.98</td>
<td>14.8</td>
<td>1.26</td>
</tr>
<tr>
<td>1m$^3$ Cylinder</td>
<td>10kJ Pyrotechnic</td>
<td>600</td>
<td>600</td>
<td>14</td>
<td>0.92</td>
<td>15.5(12.8)</td>
<td>0.78</td>
</tr>
<tr>
<td>6.2m$^3$ Cylinder</td>
<td>100J Capacitive Spark</td>
<td>860</td>
<td>860</td>
<td>6</td>
<td>0.89</td>
<td>17.8</td>
<td>0.83</td>
</tr>
</tbody>
</table>

TABLE 6.6.

+ average measurement of K

From these data certain salient facts can be extracted:

(i) the 1.23dm$^3$ and 1.75dm$^3$ laboratory scale apparatus gave dust explosibility results which are some 3 - 4 times less severe than results obtained in the standard 1m$^3$ apparatus;
(ii) for a given ignition delay, a higher spark ignition energy results in a marginally more violent explosion;

(iii) discrete ignition procedures enable the dust cloud to be ignited in a more turbulent condition (lower $t_v$), and thus result in more intense dust explosions;

(iv) even with discrete 100J spark ignition at the optimum ignition delay in the 1.75dm$^3$ 1:1 aspect ratio apparatus, the resultant explosibility determination was very significantly lower than that attained in the standard 1m$^3$ apparatus;

(v) with the correct choice of experimental procedure cellulose dust K values determined from 43dm$^3$ tests were commensurate with those obtained in the 1m$^3$ apparatus, but there was a significant disparity in the corresponding $\alpha$ determinations;

(vii) the 6.2m$^3$ dust explosion test procedure produced slightly more intense cellulose dust explosions than those obtained in the standard 1m$^3$ apparatus.

There are two contributory factors to the disparity in dust explosibility determinations in the Hartmann tube and 1m$^3$ apparatus:

(i) wall quenching, inhomogeneous dust dispersion and the inherently low turbulence levels in the Hartmann tube result in an underestimate of K by a factor $\sim 2.5$, see section 6.1.2;
(ii) the use of a sustained ignition source can lead to explosibility
data that is difficult to interpret because $t_v$ is not controlled,
see section 6.1.2.2.

Wall quenching is reduced with the 1:1 aspect ratio tube, but the lower
turbulence level and the inhomogeneous dust dispersion remains, thus this
apparatus also results in a severe underestimate of cellulose dust explosibil-
ity, compared to a 1m$^3$ determination.

The 43dm$^3$ apparatus test methodology was adjusted empirically so that
a K determination in this apparatus was commensurate with a corresponding
measurement in the 1m$^3$ apparatus, see section 6.1.3.2. The early stages
of explosion development in this apparatus were more intense than was re-
corded in 1m$^3$ trials, which is reflected by the disparity in the $\alpha_S$ determin-
ations. The tangent to the inflexion in the P/t record of a 1m$^3$ dust explosion
result is drawn at a higher pressure than the corresponding tangent for the P/t
record of a 43dm$^3$ dust explosion result. This occurs because the smaller
explosion chamber produces more wall quenching of a turbulent dust explosion
than occurs in the larger volume vessel.

Comparable industrial dust explosibility measurements were undertaken in
both the standard Hartmann apparatus (hot coil ignition) and the 43dm$^3$
apparatus (spray ring dispersions, $t_v = 265$ms). The results are summarised
in Table 6.7. below.

+ 100J spark or 1kJ pyrotechnic ignition.
<table>
<thead>
<tr>
<th>DUST SAMPLE</th>
<th>K (MPa m s$^{-1}$)</th>
<th>K RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HARTMANN TUBE 43dm$^3$ APPARATUS</td>
<td></td>
</tr>
<tr>
<td>Magnesium Stearate</td>
<td>8.8</td>
<td>23.7</td>
</tr>
<tr>
<td>Phenolic Resin</td>
<td>7.1</td>
<td>19.7</td>
</tr>
<tr>
<td>Cellulose</td>
<td>3.6</td>
<td>12.5</td>
</tr>
<tr>
<td>Pharmaceutical Product</td>
<td>1.9</td>
<td>10.6</td>
</tr>
<tr>
<td>Gum Arabic</td>
<td>1.7</td>
<td>10.9</td>
</tr>
<tr>
<td>Avicel</td>
<td>1.4</td>
<td>11.1</td>
</tr>
<tr>
<td>Spray Dried Coffee</td>
<td>0.58</td>
<td>17.3</td>
</tr>
<tr>
<td>Dried Milk Granules</td>
<td>0.40</td>
<td>9.2</td>
</tr>
</tbody>
</table>

**TABLE 6.7.**

These data emphasise the limitations of the standard Hartmann dust explosibility measurement procedure. There is no simple scaling factor. However, the Hartmann test is more likely to underestimate the explosibility of the less explosive dusts.

The experimental procedure designed for dust dispersion in the 6.2m$^3$ vessel resulted in an average cellulose dust explosibility determination some 10% more intense than the maximum value obtained in the 1m$^3$ apparatus. A small increase in $t_v$ could compensate for this discrepancy, see Figure 42. Table 5.33 demonstrates that dust explosibility determinations in this vessel were highly reproducible: $\pm 4\%$ for a $P_{\text{max}}$ measurement, $\pm 17\%$ for a $K$ determination, and $\pm 14\%$ for an $\alpha_S$ determination.
6.1.4. Influence of Turbulence on Dust Explosibility

The relationships between ignition delay, \( t_v \), and turbulence (in as much as it is reflected by increased \((dP/dt)_{max}^{\prime}\) values) has been established for both gas and dust explosions in the different test apparatus. Since a quiescent dust explosion is not achievable practically, direct comparison between gas and dust data is not possible. The \( S_g \) calibration curves defined in Figure 58 are obviously not valid for turbulent dust explosions, since such values would imply a negative value for \( \alpha S_u \).

The influence of turbulence on dust explosibility can be inferred by considering the ratio of test results at specific ignition delays. Comparable dust and gas data extracted from Tables 5.15 and 5.22 are presented as ratios in Table 6.8.

<table>
<thead>
<tr>
<th>EXPLOSIBLE FUEL</th>
<th>((dP/dt)_{max}^{\prime} t = 265\text{ms}^{-1})</th>
<th>((dP/dt)_{max}^{\prime} t = 210\text{ms})</th>
<th>((dP/dt)_{max}^{\prime} t = 320\text{ms})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DUST</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cellulose</td>
<td>37</td>
<td>1.18</td>
<td>0.77</td>
</tr>
<tr>
<td>Magnesium Stearate</td>
<td>77</td>
<td>1.16</td>
<td>0.69</td>
</tr>
<tr>
<td>Fenclofenac</td>
<td>30</td>
<td>1.14</td>
<td>0.79</td>
</tr>
<tr>
<td>Phenolic Resin</td>
<td>56</td>
<td>1.06</td>
<td>0.55</td>
</tr>
<tr>
<td>Gum Arabic</td>
<td>27</td>
<td>1.31</td>
<td>0.62</td>
</tr>
<tr>
<td>GAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Vol % CH(_4)</td>
<td>123</td>
<td>1.17</td>
<td>0.77</td>
</tr>
<tr>
<td>14 Vol % 70/30 CH(_4)/H(_2)</td>
<td>143</td>
<td>1.18</td>
<td>0.76</td>
</tr>
</tbody>
</table>

TABLE 6.8.
It is evident that the explosibility ratios of both gases and dusts are similar, although the range of \((dP/dt)_{\text{max}}\) values vary from 27 to 143 MPa s\(^{-1}\).

This analysis suggests that:

(i) the influence of turbulence on dust explosibility is, to a first approximation, a simple scaling factor which is independent of the 'absolute' explosibility of the dust;

(ii) the influence of turbulence on dust explosibility may be estimated, to a first approximation, using a calibration determined from comparable gas explosion tests.

Turbulent gas explosion data pertinent to the 43dm\(^3\) and 1m\(^3\) apparatus demonstrate that at the 'standard' ignition delay times of 265ms and 600ms used for dust explosibility measurements similar levels of turbulence prevail, see Figure 58. The turbulent gas explosion \(S_g\) ratios determined for the 43dm\(^3\) apparatus are:

\[
\begin{align*}
\frac{S_g(t = 210\text{ms})}{S_g(t = 265\text{ms})} & = 1.21 \\
\frac{S_g(t = 320\text{ms})}{S_g(t = 265\text{ms})} & = 0.71
\end{align*}
\]

which are in general agreement with the \((dP/dt)_{\text{max}}\) ratios reported in Table 6.8 for both gas and dust explosion tests. Although turbulent gas explosion tests cannot provide absolute \(S_g\) values which are meaningful for corresponding dust explosion tests, because the mechanisms of combustion wave propagation are quite different, the ratio of \(S_g\) values determined from turbulent gas explosion tests provide the means of determining the influence of turbulence on dust explosibility. From equation (42) an estimate of the
theoretical 'quiescent' dust/air suspension burning velocity, \( S_u \), can be made. For a homogeneous suspension of cellulose dust at the most explosible dust concentration, the quiescent cellulose dust/air burning velocity \( S_u \approx 0.55 \text{ m s}^{-1} \). Values of \( S_u \approx 0.55 \text{ m s}^{-1} \) reported for turbulent cellulose dust explosions must reflect inhomogeneous dust dispersion and/or reduced dust/air concentrations. These effects are particularly prevalent at extended ignition delays.

In practice, determination of \( S_u \) for an explosible dust is of academic interest only, and the turbulent burning velocity \( \alpha S_u \) provides the basis for dust explosion hazard assessment.

6.1.5. Explosion Hazard Assessment

Quantification of the potential explosion hazard associated with flammable gases and combustible dusts in industrial applications is a pre-requisite to the design of active explosion protection measures. The potential explosion intensity is dependent both on the nature of the explosible material and the conditions prevailing in normal, or abnormal, working of the industrial process. In particular, turbulence and air-flow levels within a plant processing segment can have a major influence on the resultant explosion intensity of a combustible material.

Dust explosibility measurement is undertaken at a specific turbulence level defined by the test methodology. Such a determination may represent an underestimate, or an overestimate, of the potential explosion intensity that can occur in a particular industrial processing segment. Hence a dust explosibility determination provides a measure of the relative explosion intensity of the dust sample dispersed as a cloud in air but does not quantify the actual hazard per se.
One philosophy of safety, is to seek to quantify the severest explosion experimentally possible with the particular dust sample and to accept this determination as an estimate of the potential explosion hazard. In practice, this philosophy precludes the application of conventional active explosion protection measures for many of the commonly encountered explosible materials, because the potential explosion hazard would be assessed as 'too severe'. Plant operators would be required to install alternative safety measures such as inertisation. This philosophy, therefore, can impose severe practical and economic constraints on industry.

An alternative approach is to estimate the potential explosion hazard from a knowledge of both the plant operating conditions and the measured explosibility of the material. Such an approach to safety demands a measure of considered judgement. For example, an experimental dust dispersion procedure which rapidly injects the material into a test vessel through multiple nozzles can be considered representative of the conditions prevailing in micronisers and grinders, but an overestimate of the turbulence level prevailing in the head space of gravity fed silos. The empirical turbulence parameter, $\alpha$, provides an a priori means of classifying explosion hazard. From the results of this research the following categories of explosion hazard are suggested:

<table>
<thead>
<tr>
<th></th>
<th>GAS EXPLOSIONS</th>
<th>DUST EXPLOSIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>High turbulence</td>
<td>$\alpha \approx 5.0$</td>
<td>$\alpha \approx 2.0$</td>
</tr>
<tr>
<td>Medium turbulence</td>
<td>$\alpha \approx 3.5$</td>
<td>$\alpha \approx 1.5$</td>
</tr>
<tr>
<td>Low turbulence</td>
<td>$\alpha \approx 2.5$</td>
<td>$\alpha \approx 1.2$</td>
</tr>
<tr>
<td>Quiescent conditions</td>
<td>$\alpha \approx 1.0$</td>
<td>---</td>
</tr>
</tbody>
</table>

Dust explosibility determinations in the standard 1m$^3$ apparatus are considered to be representative of the severest conditions of turbulence encountered generally. Such data can be scaled to other volumes and conditions of turbulence using the revised cube law derived in section 3.1.3., see equation (25). Explosion protection measures would be designed for each industrial application, based on the meaningful estimates of the worst case explosion hazards. The designed explosion protection systems would include significant safety margins.

6.1.6. Correlation between Theory and Experiment

The isothermal model of explosion pressure development described in section 3.1.1. has been used as a basis for all $S_u$ and $\kappa S_u$ data reported above. Figure 63 presents experimental plots of $dP/dt$ against $(1 - P_o/P)^3 P$ for $\sim 9.5$ Vol $\%$ quiescent CH$_4$-air explosions in the five test apparatus evaluated. Good straight line fits result and the calculated burning velocity of 9.5 Vol $\%$ CH$_4$-air is invariant essentially over the test apparatus volume range.

Theoretical computer generated pressure/time curves of gas and dust explosions, based on equation (19), are compared with corresponding experimental records in Figure 64. Good agreement is evident during the early stages of explosion pressure development ($P < 0.2$ MPa). Hence the simple isothermal model can form the foundation for a theoretical evaluation of explosion suppression system performance.

Explosion hazard assessment provides the necessary data to permit computer simulation of the pressure/time history of a worst case explosion of the combustible material in the pertinent industrial environment.
6.2. Explosion Suppressants

The literature identifies both physical and chemical mechanisms of flame inhibition and suppression. The relative inhibition effectiveness of various agents against cellulose dust explosions in the Hartmann tube can be ascertained from the results presented in section 5.2., see Figures 43 - 45. Table 6.9. compares the measured inhibiting concentrations of those agents with their contribution to the heat abstraction capacity of the mass of suppressant discharged into the system $q_h$. This parameter reflects the heat abstraction potential of the suppressant agent, see section 3.2.

<table>
<thead>
<tr>
<th>SUPPRESSANT AGENT</th>
<th>INHIBITING CONCENTRATION</th>
<th>MASS g</th>
<th>SPECIFIC HEAT J g$^{-1}$ K$^{-1}$</th>
<th>$q_h$ J K$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WEIGHT %</td>
<td>VOL %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$</td>
<td>51</td>
<td>42</td>
<td>1.32</td>
<td>0.84</td>
</tr>
<tr>
<td>N$_2$</td>
<td>49</td>
<td>51</td>
<td>1.03</td>
<td>1.04</td>
</tr>
<tr>
<td>Halon 1211 (vapour)</td>
<td>41</td>
<td>7.5</td>
<td>0.88</td>
<td>0.45</td>
</tr>
<tr>
<td>Halon 1301 (vapour)</td>
<td>40</td>
<td>7.5</td>
<td>0.80</td>
<td>0.46</td>
</tr>
<tr>
<td>Mono-ammonium phosphate</td>
<td>27</td>
<td>-</td>
<td>0.28</td>
<td>1.85</td>
</tr>
<tr>
<td>China Clay</td>
<td>70</td>
<td>-</td>
<td>0.74</td>
<td>0.73</td>
</tr>
</tbody>
</table>

**TABLE 6.9.**

From Table 6.9. certain conclusions can be drawn on the inhibiting effectiveness of these agents against cellulose dust explosions:

(i) the inhibiting concentrations (weight and vol %) of the 'inert' gases, CO$_2$ and N$_2$, were greater than the corresponding inhibiting concentrations of Halon vapours;
(ii) the Halon agent contribution to the heat capacity of the system is only \( \sim 40\% \) of that found with the 'inert' gases;

(iii) the mono-ammonium phosphate powder suppressant and the 'inert' powder, china clay exhibited very similar contributions to the heat capacity of the system;

(iv) the heat abstraction potential of the 'inert' gases was greater than that of the powder suppressant agents.

These results demonstrate a chemical influence of the Halon vapours superimposed over their heat abstraction influence. It is deduced that Halon vapours are more effective than 'inert' gases as inerting agents. In practice, it is difficult to separate the thermodynamic heat abstraction capability of an agent from the kinetics of heat transfer. It would be expected that Halon liquid sprays used as explosion suppressants will demonstrate a larger thermal influence than is suggested by the data in Table 6.9, because of the kinetics of droplet evaporation and the corresponding latent heat of vaporisation of the liquid suppressant. The thermal contribution to explosion suppression will be more prevalent with the less volatile Halons. Explosion suppression results presented in Tables 5.42 and 5.44 have demonstrated that the more volatile Halon 1211 is a less effective explosion suppressant than Halon 1011.

The argument, see section 2.3.2., that a mono-ammonium phosphate based powder suppressant has a significant chemical influence is not substantiated by these results. Its effectiveness is similar to that of an inert powder, that is it acts primarily as a diluent and thermal quenching agent. The explosion suppression result obtained inadvertently, see section 5.4.3.3., whereby
12 kg of mono-ammonium phosphate powder suppressant was released into the 6.2 m³ vessel ~250 ms after an unsuppressed cellulose dust explosion provided an insight into the action of this agent. The resultant pressure/time record in this experiment is shown in Figure 65. The explosion pressure was reduced rapidly from ~0.84 MPa to ~0.42 MPa in ~25 ms upon injection of the suppressant. This effect must be that of heat abstraction, since combustion would have ceased at \( \sim P_{\text{max}} \). The theoretical heat abstraction consequence of the injection of the suppressant can be calculated from the thermodynamic data presented in Appendix 2. An explosion pressure of 0.84 MPa corresponds to a system temperature of \( \sim 1400 \text{K} \), and to a system energy of \( \sim 14.2 \text{MJ} \). The heat capacity of 12 kg of the mono-ammonium phosphate suppressant is \( 22 \text{kJ K}^{-1} \). Hence injection of the suppressant should result in a final temperature of \( \sim 640 \text{K} \) and a corresponding pressure of 0.39 MPa. This theoretical value is in good agreement with the observed pressure of 0.42 MPa. Note that the pressure drop occurred in ~25 ms which demonstrates the fast and efficient heat abstraction capability of this powder suppressant.

The relative effectiveness of the suppressants Halon 1011, Halon 1211, water and mono-ammonium phosphate powder against both gas and dust explosions have been evaluated experimentally, see section 5.4. The implications of these results are discussed in section 6.4.

6.3. Explosion Suppressors

The suppressant discharge characteristics of both hemispherical and high rate discharge (HRD) suppressors were measured to provide basic data necessary to test the theoretical model of explosion suppression described in section 3.4.
6.3.1. **Hemispherical Suppressors**

The discharge characteristics of hemispherical type suppressors described in section 2.4.1. are summarised in Figure 46. These suppressors deliver liquid suppressant very rapidly. They have a negligible activation time, and a 180° suppressant discharge profile; but a limited throw.

6.3.2. **High Rate Discharge (HRD) Suppressors**

The results of section 5.3. have identified three regimes of suppressant discharge from HRD suppressors of the type shown in Plate IIb.

\[
\begin{align*}
  t_o' &\rightarrow t_o & \text{initial burst of suppressant} \\
  t_o &\rightarrow t_1 & \text{bulk discharge of suppressant} \\
  t_1 &\rightarrow t_2 & \text{discharge of remaining suppressant}
\end{align*}
\]

The \( t_o' \rightarrow t_o \) regime occurs only for the liquid fill HRD suppressors of this specific construction. The liquid suppressant between the frangible disc and the detonator is propelled ahead of the bulk of suppressant by the hydraulic shock wave created by the explosive. The same shock wave momentarily delays the bulk suppressant discharge because it opposes the propelling agent driving force. At time \( t_1 \), the propelling agent 'punches through' the remaining suppressant charge.

6.3.2.1. **Standard HRD Suppressors**

All experimental work reported in this thesis was undertaken using Graviner explosion suppressors. The measured discharge characteristics of the standard Graviner HRD suppressors are presented in section 5.3.2.1. These suppressors demonstrate a significant activation time. The use of a 90°
elbow increased the bulk discharge time, $t_1 - t_o$, of the $3dm^3$ suppressor * by approximately 10ms. The use of a longer spreader also increased the suppressant discharge time. Comparisons between the data recorded for the standard suppressor range of $3dm^3$, $10dm^3$ and $35dm^3$, see Tables 5.35. and 5.36., are confounded by the different fill ratios used as standard in the Graviner suppressors:

- $3dm^3$ HRD - fill ratio 60%
- $10dm^3$ HRD - fill ratio 53%
- $35dm^3$ HRD - fill ratio 81%

6.3.2.2. HRD Suppressor Parameters

The optimum fill ratio is inevitably a compromise between the quantity of suppressant discharged in the bulk $t_o \rightarrow t_1$ regime and the suppressant mass discharge rate.

Figure 49 indicates that the optimum fill ratio for the $3dm^3$ HRD suppressor is 55 – 60%. It is evident from the suppressor canister depressurisation curves that the maximum depressurisation rate increased with fill ratio, thus reflecting the reducing effectiveness of the propelling agent to expel the suppressant, see Figure 50.

Figure 51 shows that the suppressant discharge time decreased with increasing propelling agent pressure and high speed cine records demonstrated that a greater suppressant discharge velocity occurred at the higher propelling agent pressure.

* The standard nomenclature defines an HRD suppressor by its suppressant capacity.
Figure 52 shows, not unexpectedly, that the suppressant discharge times decreased with an increase in the suppressor outlet orifice diameter. The measured initial suppressant discharge velocities were found to be independent of the suppressor outlet area. The canister depressurisation rate increased with an increase in the suppressor outlet orifice diameter.

6.3.3. Comparison of Results with Theory

Comparisons between measurement and theory is not valid beyond time \( t_1 \) because of the significant nitrogen 'punch through' that occurs. The observations summarised in section 6.3.2.2. are all consistent with the very simple theory of an HRD suppressor discharge described in section 3.2.2. The discharge rate is proportional to the outlet area \( A \) and to the root of the propelling agent pressure, \( \sqrt{\frac{P_{N_2}}{\rho}} \), as suggested by the theory.

The measured 3dm\(^3\) HRD suppressor discharge characteristic compares well with theoretically predicted performance for \( t < t_1 \), see Figures 5 and 6. The measured initial discharge velocity was 43 m s\(^{-1}\) and 80 m s\(^{-1}\) for \( P_{N_2} \) of 2 and 6 MPa respectively. This is in good agreement with corresponding theoretical values of 46 m s\(^{-1}\) and 79 m s\(^{-1}\) derived from equation 27. Agreement between theory and experiment breaks down at \( t > t_1 \).

Figure 66 compares the theoretical discharge characteristics of various HRD suppressors. The 19mm diameter single and dual exit type suppressors have much longer bulk discharge times, but higher initial discharge velocities than the 76mm diameter single exit type suppressors; however it is probable that a greater percentage of suppressant will be discharged in the bulk \( t_0 \rightarrow t_1 \), regime with the 19mm diameter type suppressors. The addition of peripherals, such as connecting pipework, elbows and spreaders will reduce the discharge rate and thus increase the suppressant discharge time.
6.3.4. **System Analogues**

Simple mathematical analogues of a suppressor discharge can be defined from the experimental measurements of \( t_0, t_1, t_2 \) and \( R_1 \) and \( R_2 \), or from theoretical interpolation of these data.

![Diagram](image.png)

Pertinent suppressor discharge data are summarised in Tables 5.32 - 5.34. These analogues, coupled with the suppressant throw characteristics defined in Figures 46 and 48 were used in the explosion suppression model described in section 3.4.

6.4. **Explosion Suppression**

Experimental trials provide essential information on the efficacy of explosion suppression measures. The results of explosion suppression tests on gas and dust explosions in 1m\(^3\) and 6.2m\(^3\) vessels reported in section 5.4. have determined the relative effectiveness of the three suppressants, mono-ammonium phosphate powder, water, and Halon 1011. These results provide a foundation to test the validity of the theoretical model described in section 3.4.

6.4.1. **Suppression of Quiescent Gas Explosions**

The explosion suppression trials on quiescent gas explosions, see Table 5.41 and 5.45, have established certain experimental facts:
(i) Water is not an effective suppressant of gas explosions;
(ii) At the lower detection pressures ($P_A < 10$ kPa) both mono-ammonium phosphate powder and Halon 1011 are equally effective suppressants;
(iii) More effective suppression is attained with the use of a larger number of smaller suppressors;
(iv) More effective suppression is attained with the use of a higher propelling agent pressure;
(v) At the higher detection pressures, Halon 1011 can fail to suppress the explosion; the resultant overpressure exceeds that of a corresponding unsuppressed explosion.

Typical pressure/time records obtained in explosion suppression trials are sketched in Figures 53 and 54. Most commonly, curves of type $S_2$ were obtained. Curves of type $S_1$ were only recorded in experiments with a very low detection pressure; the pressure continues to rise after the explosion has been suppressed effectively because:

(i) The suppressant propelling agent continues to be discharged into the test chamber;
(ii) Volatile liquid suppressants have a significant vapour pressure.

This second pressure rise is usually slow compared to the suppressed explosion event. Conventionally, the suppressed explosion pressure, $P_{RED}$, is reported as the greater value of the measurements $P_R$ or $P_R^*$ defined in Figures 53 and 54.
The influence of propelling agent pressure, $P^N_2$, on the suppression effectiveness of mono-ammonium phosphate powder and Halon 1011 in the 1m³ apparatus is demonstrated in Figure 67. At the higher detection pressures, suppression was more effective with the higher propelling agent pressures because the suppressant was injected more rapidly into the growing fireball. However, at the lower detection pressures, the higher propelling agent pressure produced an increased suppressed explosion pressure, $P^\text{RED}$, because of the significant contribution of this propelling agent pressure to the total system pressure.

Figure 68 shows that more effective suppression was achieved with the higher propelling agent pressure, $P^N_2 = 6 \text{ MPa}$, for all $P_A \geq 18 \text{ kPa}$. Inevitably higher detection pressures resulted in less effective suppression and for $P_A \geq 50 \text{ kPa}$ and $P^N_2 = 2 \text{ MPa}$, 4kg m⁻³ of Halon 1011 failed to suppress a 15 Vol% 70/30 CH₄/H₂ explosion in the 1m³ vessel (Tests 20 and 21). Halon 1011 also proved ineffective in 6.2m³ trials; a concentration of 2.9kg m⁻³ failed to suppress 9.5 Vol% CH₄/air explosions for all $P_A \geq 25\text{ kPa}$ (Tests 99 and 100).

Historically, mono-ammonium phosphate powder and Halon 1011 suppressants were introduced into different market areas and installed with different operational requirements:

- **Powder system**  
  $P_A \propto 10\text{kPa}, \quad P^N_2 \approx 6 \text{ MPa} \quad \rightarrow \quad P^\text{RED} \leq 0.1 \text{ MPa}$

- **Halon system**  
  $P_A \leq 3.5\text{kPa}, \quad P^N_2 \approx 2 \text{ MPa} \quad \rightarrow \quad P^\text{RED} \leq 0.025 \text{ MPa}$

Figure 69 shows that these 'standard' systems were effective in suppressing 70/30 CH₄/H₂ explosions in the 1m³ apparatus with a $\geq 50\%$ reduction in the nominal system suppressant concentration of 4kg m⁻³. It can be seen that the $P^\text{RED}$ achieved with the standard Halon system was lower than that achieved with the standard powder system, largely as a consequence of the lower detection pressure employed with the Halon system.
Explosion suppression trials in the 6.2m$^3$ vessel demonstrated that three 3dm$^3$ HRD suppressors were more effective than one 10dm$^3$ HRD suppressor, compare results of Tests 97, 98 and 99 with Test 102 in Table 5.45. This demonstrates the importance of the increased suppressant mass discharge rate achieved by using a larger number of smaller HRD suppressors to attain a particular suppressant design concentration. It is worthy of note that two 5dm$^3$ hemispherical suppressors (Test 105) did not suppress a comparable explosion. As the hemispherical suppressors have a superior suppressant discharge characteristic, this was an unexpected result. A possible explanation is identified in section 6.4.5.2. below.

6.4.2. Suppression of Turbulent Gas Explosions

It has been established in section 6.1.1. that a preset ignition delay, $t_v$, defines a specific level of turbulence for turbulent gas explosions. Turbulent gas explosion suppression trials were undertaken only in the 1m$^3$ apparatus, see Table 5.42.

Figure 70 presents the relationship between the measured suppressed explosion pressure, $P_{RED}$, and the corresponding unsuppressed explosion turbulent burning velocity $\alpha S_u$. It is evident that the mono-ammonium phosphate system ($P_A = 0.01$ MPa, $P_{N_2} = 6$ MPa) suppressed all turbulent gas explosions with $\alpha S_u < 2.2$ m s$^{-1}$, and that the corresponding Halon 1011 system suppressed all turbulent gas explosions with $\alpha S_u < 1.5$ m s$^{-1}$. The distinction in effectiveness between the two suppressants is increased further since 'failed' Halon suppressions resulted in $P_{RED}$ values greater than the corresponding unsuppressed $P_{max}$ values.
Interpolation from the experimental relationship between $\alpha_S$ and $K$, see Table 5.2., enables the limits of effectiveness of these two specific explosion suppression systems ($P_A = 0.01$ MPa, $P_{N_2} = 6$ MPa) to be defined for gaseous explosion hazards in volumes of nominally $1m^3$:

- **Powder system**: $K < 45$ MPa m$^{-1}$ s$^{-1}$
- **Halon 1011 system**: $K < 30$ MPa m$^{-1}$ s$^{-1}$

Thus, mono-ammonium phosphate powder suppressant is more effective than Halon 1011, and the latter can result in 'critical failure' as predicted by the thermal model described in section 3.4.

### 6.4.3. Suppression of Dust Explosions

Explosion suppression trials in the 1$m^3$ apparatus were undertaken using a 10kJ pyrotechnic igniter. Since the explosion energy corresponding to a typical low detection pressure of $\sim 3.5$ kPa is only $11kJ m^{-3}$ it is evident that this pyrotechnic igniter represents a significant contribution to the total system energy at detection. The datum experiments reported in section 5.4.2.1. show that the overpressure created by the pyrotechnic igniter in the 1$m^3$ apparatus was $\sim 6kPa$. Explosion suppression trials in the 6.2$m^3$ apparatus used 100J spark ignition to ensure that the effectiveness of a sensitive explosion suppression system was not masked.

Results of explosion suppression trials in the 1$m^3$ apparatus are presented graphically in Figures 71 and 72, see Tables 5.43 and 5.44. These results show that:
(i) with a high propelling agent pressure, mono-ammonium phosphate powder, water, and Halon 1011 were equally effective against coal dust explosions;

(ii) water was the most effective suppressant against cellulose dust explosions, although one poor result was obtained (Test 63);

(iii) at the lower propelling agent pressure of 2MPa, Halon 1011 was ineffective against cellulose dust explosions;

(iv) 'failed suppressions' can result with Halon 1011.

Mono-ammonium phosphate powder, and Halon 1011 suppressants were originally introduced into different market areas and installed with different operational requirements:

**Powder system**

- $P_A \lesssim 10$kPa, $P_{N_2} \approx 6$ MPa

**Halon system**

- $P_A \leq 3.5$kPa, $P_{N_2} \approx 2$ MPa

$\rightarrow P_{RED} \leq 0.1$ MPa

$\rightarrow P_{RED} \leq 0.025$ MPa

Figure 73 shows that these 'standard' systems were effective in suppressing highly turbulent cellulose dust explosions with a $\geq 50\%$ reduction in the nominal suppressant design concentration of 4kg m$^{-3}$. However, the results of Figure 72 shows that a very small increase in the detection pressure of the standard Halon system would result in 'critical' failure. The difference in effectiveness between the two systems is less pronounced than was found with gas explosion trials, compare Figures 69 and 73. The poor performance of both Halon 1011 and Halon 1211 against 1m$^3$ turbulent cellulose dust explosions may have been partially accentuated by the 10kJ pyrotechnic igniter.
Results of 6.2m$^3$ dust explosion suppression trials are presented in Table 5.46. Figure 74 demonstrates the relative effectiveness of mono-ammonium phosphate, water and Halon 1011 suppression systems against cellulose dust explosions. These results show that:

(i) both mono-ammonium phosphate and water can suppress effectively a highly turbulent cellulose dust explosion in this large volume;

(ii) the Halon 1011 suppression system was quite ineffective against an explosion of this intensity and scale;

(iii) the Halon 1011 suppression system was demonstrated only to be effective against a low turbulence cellulose dust explosion, see Test 119;

(iv) the choice of suppression system hardware had a major influence on the level of explosion suppression achieved.

12kg of a mono-ammonium phosphate based powder suppressant suppressed effectively a turbulent cellulose dust explosion in the 6.2m$^3$ vessel, whereas 24kg (12dm$^3$) of Halon 1011 proved quite ineffective. Water was less effective than the mono-ammonium phosphate powder suppressant. 12kg (12dm$^3$) of water failed to suppress the explosion. At a detection pressure $P_A \leq 16kPa$, 30kg (30dm$^3$) of water suppressed the cellulose dust explosion when discharged from three single exit (76mm diameter) HRD suppressors; but did not suppress the explosion when discharged from one larger single exit (76mm diameter) HRD suppressor. Halon 1011 explosion suppression measures were only effective against low turbulence cellulose dust explosions
in the 6.2m³ vessel. A Halon system comprising of two hemispherical suppressors and two HRD suppressors proved more effective than a system comprising of HRD suppressors alone. This reflects the influence of the higher suppressant discharge rate achieved with hemispherical suppressors. This is contrary to the findings in 6.2m³ quiescent gas explosion suppression trials, see section 6.4.1. A possible explanation is identified in section 6.4.5.2. below.

6.4.4. International Collaborative Research Programme

The efficacy of explosion suppression using a single HRD suppressor (76mm diameter single exit) for both gas and dust explosions in a 1m³ vessel is demonstrated by the results presented in section 5.2.2. These tests formed part of an International collaborative research programme, see section 1.3. Comparable explosion suppression trials undertaken by other workers are summarised in Appendix 1. Table 6.10. presents an overall comparison of the results obtained in these trials:

<table>
<thead>
<tr>
<th>EXPLOSIBLE FUEL</th>
<th>EXPLOSION SUPPRESSANT</th>
<th>P_A kPa</th>
<th>V=1m³, one dual exit 19mm HRD</th>
<th>V=1m³, one single exit 76mm HRD</th>
<th>V=3.8m³, two single exit 76mm HRDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>'PROPANE' GAS</td>
<td>Water</td>
<td>10</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Halon</td>
<td>10</td>
<td>FAIL</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td></td>
<td>1011</td>
<td>30</td>
<td>FAIL</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td>Powder</td>
<td>10</td>
<td>****</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>CELLULOSE DUST</td>
<td>Water</td>
<td>10</td>
<td>***</td>
<td>***</td>
<td>****</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>*</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td>Halon</td>
<td>10</td>
<td>*</td>
<td>***</td>
<td>****</td>
</tr>
<tr>
<td></td>
<td>1011</td>
<td>30</td>
<td>FAIL</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td>Powder</td>
<td>10</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>**</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

**FAIL** \( P_{\text{RED}} \gg P_{\max} \)

**** \( P_{\text{RED}} < 30kPa \)

*** \( 30kPa < P_{\text{RED}} \leq 100kPa \)

** \( 100kPa < P_{\text{RED}} \leq 300kPa \)

* \( 300kPa < P_{\text{RED}} < P_{\max} \)

a \( P_{N_2} = 12 \text{ MPa} \)

b \( P_{N_2} = 6 \text{ MPa} \)

TABLE 6.10
In general the single exit (76mm diameter) HRD suppression system was more effective than the dual exit (19mm diameter) HRD suppression system. More effective suppression was achieved in the larger volume. This conclusion is contrary to that inferred from the available explosion suppression results obtained in 1m$^3$ and 6.2m$^3$ vessels reported in this thesis. Thus there is some conflict between the test results of the two series of trials. Note that the propelling agent pressure used in the 1m$^3$/6.2m$^3$ comparable trials was 2 MPa, rather than the 6 MPa used for the 1m$^3$/3.8m$^3$ comparable trials. Furthermore, the explosion intensity of turbulent cellulose dust was considerably greater in the 6.2m$^3$ vessel, because a more turbulent dust cloud was produced by the chosen dust dispersion procedure. The converse was true in the 3.8m$^3$ vessel.

Table 6.10 shows that the effectiveness of particularly Halon 1011 as an explosion suppressant was dependent on the choice of explosion suppressor, thus demonstrating the importance of a high suppressant mass discharge rate. Figure 75 presents comparable $P_{RED}$ data obtained in the 1m$^3$ apparatus with the different explosion suppressors. The 76mm diameter single exit suppressor was more effective than the 19mm diameter dual exit suppressor at the higher detection pressures, but marginally less effective at the lower detection pressures. The dual exit (19mm diameter) suppressor has a higher initial discharge velocity than the single exit (76mm diameter) suppressor, but a lower mass discharge rate, see Figure 66. Therefore at a low detection pressure, where the fireball is spatially small and the system energy content is low, the dual exit (19mm diameter) suppressor can prove more effective because it delivers a small amount of the suppressant charge to the explosion faster than does the single exit (76mm diameter) suppressor. The superior suppressant mass discharge characteristic of the latter ensures that, overall, it forms the basis of the most effective systems.
6.4.5. Evaluation of Explosion Suppression Model

Section 3.4. describes a mathematical model to estimate the final pressure obtained in a suppressed explosion event. This estimate of $P_{RED}$ does not take account of the suppressant vapour pressure or of the pressure rise resulting from the suppressor(s) propelling agent. The parameters used for computer estimates of $P_{RED}$ are listed in Appendix 4.

6.4.5.1. 1m³ Explosion Suppression Trials

The extensive series of experiments undertaken in the 1m³ apparatus, see section 5.4., provide a useful base to test the validity of the mathematical model. Computer estimates of $P_{RED}$ for each of the 93 tests are listed along with the experimental conditions and results in Table 5.41 - 5.44. Comparisons of theoretical and experimental $P_{RED}$ values are presented in Figures 76 and 77. With a few exceptions, the theoretical $P_{RED}$ value is higher than the experimental $P_{RED}$ value. In general, the theoretical model errs on the side of safety; the disparity between prediction and experimental measurement is greater for gas explosions than for dust explosions. In all tests where a 'failed suppression' occurred, the mathematical model predicted it. In a few instances the model has predicted 'fail suppression' where experiment has demonstrated that a measure of suppression is possible.

Figure 78 compares the theoretical and experimental $P_{RED}$ values for turbulent gas explosions of increasing severity. It is evident that the model's prediction of $P_{RED}$ errs on the side of safety and reflects the disparity in effectiveness between mono-ammonium phosphate and Halon 1011 suppressants. The theoretical curves show the regimes of reliable suppression, unreliable suppression and failed suppression. The a priori criteria of a reliable suppression demonstrates a significant margin of safety. Hence the validity of the theoretical model is established for the assessment of suppression system performance in \( \sim 1m³ \) volumes.

* see section 3.4.5.
6.4.5.2. 6.2m$^3$ Explosion Suppression Trials

A comparison of the measured and predicted $P_{\text{RED}}$ values for quiescent gas explosions in the 6.2m$^3$ vessel suggests that the theoretical estimate is too optimistic, see Table 5.45. Indeed the mathematical model predicted a reliable suppression for experiments that subsequently demonstrated a failed suppression, see Tests 99 and 105. One hypothesis for this discrepancy, with large volume quiescent gas explosion suppression, is that the suppressant discharge significantly perturbs the predicted course of the explosion, as a consequence of induced turbulence.

This hypothesis was tested by comparing the measured (dP/dt)$_{\text{max}}$ values of unsuppressed explosions with the measured (dP/dt)$_{\text{max}}$ values of corresponding 'failed suppression' events, see Table 6.11.

<table>
<thead>
<tr>
<th>V $^3$</th>
<th>EXPLOSION</th>
<th>TURBULENCE (\infty)</th>
<th>SUPPRESSION SYSTEM (dP/dt)$_{\text{max}}$</th>
<th>MPa s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Quiescent</td>
<td>1</td>
<td>NONE</td>
<td>9.8</td>
</tr>
<tr>
<td>70/30 CH$_4$/H$_2$</td>
<td></td>
<td></td>
<td>Water - 1 HRD - 2 MPa</td>
<td>26.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Water - 1 HRD - 4 MPa</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Water - 1 HRD - 6 MPa</td>
<td>42.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Halon - 1 HRD - 2 MPa</td>
<td>12.7</td>
</tr>
<tr>
<td>1</td>
<td>Turbulent</td>
<td>7</td>
<td>NONE</td>
<td>75.9</td>
</tr>
<tr>
<td>70/30 CH$_4$/H$_2$</td>
<td></td>
<td></td>
<td>Halon - 1 HRD - 2 MPa</td>
<td>53.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Halon - 1 HRD - 6 MPa</td>
<td>49.2</td>
</tr>
<tr>
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<td>Turbulent</td>
<td>4</td>
<td>NONE</td>
<td>41.9</td>
</tr>
<tr>
<td>70/30 CH$_4$/H$_2$</td>
<td></td>
<td></td>
<td>Halon - 1 HRD - 6 MPa</td>
<td>14.4</td>
</tr>
<tr>
<td>6.2</td>
<td>Quiescent</td>
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<td>NONE</td>
<td>2.8</td>
</tr>
<tr>
<td>CH$_4$</td>
<td></td>
<td></td>
<td>Water - 3 HRDs - 2 MPa</td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Water - 2 Hemis</td>
<td>15.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Halon - 3 HRDs - 2 MPa</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Halon - 2 Hemis</td>
<td>7.2</td>
</tr>
<tr>
<td>Turbulent</td>
<td></td>
<td></td>
<td>NONE</td>
<td>12.8</td>
</tr>
<tr>
<td>1</td>
<td>Cellulose Dust</td>
<td></td>
<td>Halon - 1 HRD - 2 MPa</td>
<td>8.0</td>
</tr>
<tr>
<td>6.2</td>
<td>Turbulent</td>
<td>4</td>
<td>Halon - 1 HRD - 6 MPa</td>
<td>10.5</td>
</tr>
<tr>
<td>Cellulose Dust</td>
<td></td>
<td></td>
<td>Halon - 1 HRD - 2 MPa</td>
<td>9.3</td>
</tr>
<tr>
<td>6.2</td>
<td>Turbulent</td>
<td>2</td>
<td>NONE</td>
<td>5.0</td>
</tr>
<tr>
<td>Cellulose Dust</td>
<td></td>
<td></td>
<td>Halon - 4 HRDs - 2 MPa</td>
<td>7.2</td>
</tr>
</tbody>
</table>

TABLE 6.11. * Halon 1211, other Halon tests all Halon 1011
A 'failed suppression' of a quiescent gas explosion, when water or Halon 1011 are used as the suppressant, is a significantly more violent event than the corresponding unsuppressed explosion. The converse is true for turbulent gas and dust explosions. Since both water and Halon 1011 demonstrate this effect, the increased explosion intensity that occurs with the quiescent gas explosion must be a consequence of induced turbulence, and not of any exothermic chemical reaction in the combustion zone. The data of Table 6.11 suggest that the perturbation of the quiescent gas explosion that occurred when the explosion suppressors were discharged was equivalent to a turbulence factor $\lambda \sim 2.3$, which must come into effect only after $P_A$.

This induced turbulence parameter was included in the mathematical model as a perturbation on the burning velocity $S_u$ occurring at the time corresponding to the injection of suppressant into the vessel:

$$t_A + t_\xi + t_C', \text{ see Figure 7. Thus for }$$
$$t < (t_A + t_\xi + t_C) = S_u \Rightarrow S_u$$
$$t \geq (t_A + t_\xi + t_C) = S_u \Rightarrow 2.3 S_u$$

This induced turbulence has a greater influence on the estimate of $P_{\text{RED}}$ in larger test volumes because of the longer time intervals between the release of the suppressant and suppression of the explosion. Figure 79 demonstrates the influence of this induced turbulence parameter on the mathematical model nomogram.

It was found that the theoretical estimates of $P_{\text{RED}}$ listed in Table 5.41 were essentially invariant when an induced turbulence factor of 2.3 was included in the calculation, with the exception of Test 16, where an unreliable suppression was predicted theoretically. Table 6.11 shows the influence of an induced turbulence factor of 2.3 on the theoretical estimates of $P_{\text{RED}}$ for quiescent gas explosion tests in the 6.2 m$^3$ apparatus.
![Table 6.12](image)

A better correspondence between the measured and predicted $P_{\text{RED}}$ values is evident with the induced turbulence perturbation included in the model. In practice, the usefulness of the model will be limited by the uncertainty in the choice of the induced turbulence factor. Test 105 refers to explosion suppression with hemispherical suppressors, and the data of Table 6.11 points to an induced turbulence factor greater than the value of 2.3 estimated for HRD suppressors. Thus, the prediction of $P_{\text{RED}}$ for Test 105 in Table 6.12, is somewhat optimistic.
Since applications of explosion suppression systems to 'quiescent gas' hazards are seldom encountered in industrial practice, a more systematic analysis of this problem has not been pursued, and an induced turbulence factor of 2.3 accepted as an empirical estimate for theoretical evaluations of the effectiveness of quiescent gas explosion suppression measures.

6.2m$^3$ cellulose dust explosion suppression trials, see Table 5.46, have demonstrated a general correspondence between measured and predicted $P_{RED}$ values. The limited number of turbulent dust explosion suppression results obtained in this large volume apparatus were supportive of the theoretical explosion suppression model described in section 3.4. Figure 74b shows that the predicted regimes of 'Failed Suppression', 'Unreliable Suppression', and 'Reliable Suppression' of cellulose dust explosions of differing turbulence levels, for a specific Halon 1011 explosion suppression measure, are in reasonable correspondence with experimental observations. Thus, the limits of applicability of a suppression system, determined by the model, are in reasonable agreement with those established experimentally.

6.4.5.3. Other Workers Results

Explosion suppression trials reported by other workers are listed in Appendix 1. These data provided the opportunity to evaluate further the validity of the mathematical model described in section 3.4. Computer estimates of $P_{RED}$ are listed adjacent to the corresponding results in Appendix 1.

There is a fair correspondence between the theoretical estimate, and the experimental measurement. In some instances 'Unreliable Suppression' was predicted where experiment had demonstrated a failed suppression. A 'Reliable Suppression' prediction was matched always by an experimentally observed suppression.
Figure 80 compares the theoretical and experimental $P_{\text{RED}}$ values for these tests. A much larger scatter is evident, compared to the corresponding comparison of $1\text{m}^3$ data, see Figure 77, and the theory has severely underestimated suppressed explosion pressures of seven trials. Variation in experimental conditions and less well defined data are assumed to be partially responsible for these discrepancies. The predicted $P_{\text{RED}}$ does not include the influence of the suppressor propelling agent pressure, thus the model tends to underestimate $P_{\text{RED}}$. This underestimate is predominant with the more effective (low $P_A$) explosion suppression measures.

The study has demonstrated a correlation between experimental measurement and theoretical prediction for some 75\% of the reported explosion suppression trials in $3.8\text{m}^3$ and $20\text{m}^3$ vessels.

6.4.6. Versatility and Applicability of the Model

The applicability of the explosion suppression model described in section 3.4. has been demonstrated for Halon, water and mono-ammonium phosphate powder explosion suppression systems against both gas and dust explosions in volumes ranging from $1 - 20\text{m}^3$.

An example of the computer program input and output is shown in Figure 8. The program was structured to permit either a routine appraisal of the effectiveness of any proposed explosion suppression system or a detailed evaluation of the limits of effectiveness of a range of explosion suppression systems. Thus, it can be used both as a research tool and as a design aid for industrial explosion suppression applications.
This research has appraised the problems of meaningful explosibility measurement and industrial explosion hazard assessment and has quantified the discharge characteristics of explosion suppressors as a necessary foundation for a study of explosion suppression. The work has culminated in the establishment of a large volume explosion test facility, a comprehensive series of explosion suppression trials and the development of a mathematical model for the assessment of the efficacy of explosion suppression measures. The specific findings of this study are collated below:

7.1. Explosions

7.1.1. A simple isothermal model of explosion pressure development provides an adequate basis for the prediction of an explosion pressure/time history. This model was used as the basis for computer simulation of an explosion pressure/time record in any defined volume.

7.1.2. The burning velocity, \( S_u \), determined from an explosion pressure/time record, provides a more meaningful measure of explosion severity than that provided by \( (dP/dt)_{\text{max}} \) because the latter is influenced by vessel geometry and other wall effects.

7.1.3. Quiescent gas explosion tests in volumes ranging from 1.23 dm\(^3\) to 1 m\(^3\) gave predictable and self-consistent explosion data. Comparable tests in the 6.2 m\(^3\) vessel identified a transition to a more violent combustion mechanism at specific explosion pressures during the course of the explosion. This effect was only observed at specific fuel/air ratios removed from the stoichiometric and was most pronounced with 5 Vol % \( C_3H_8 \).
7.1.4. The turbulence of the explosible mixture at ignition has a major influence on the consequential explosion intensity. The turbulence level attained with experimental dust dispersion procedures can be estimated by comparable turbulent gas explosion experiments.

7.1.5. In practice, dust explosibility is measured by igniting a pneumatically dispersed dust cloud in a closed vessel. The time interval between dust dispersion and ignition has a major influence on the resultant explosion intensity because the turbulence level decreases with increasing ignition delay.

7.1.6. A dust explosibility measurement in the standard Hartmann apparatus gives a substantial underestimate of the potential explosion intensity of the dust. This underestimate occurs because a quasi-continuous ignition source is used in the Hartmann test. Dusts which are insensitive to ignition exhibit long ignition delays, and thus explode when the dust cloud is less turbulent. In the Hartmann apparatus a dust explosibility measurement is dust cloud ignition sensitivity dependent.

7.1.7. The use of a 100J spark discrete ignition procedure in the Hartmann test resolves the major criticism of this apparatus. However, there remains a significant disparity between such Hartmann data and corresponding results in larger test apparatus because of both the small scale, the large aspect ratio, and the particular characteristics of the Hartmann dust dispersion procedure.
A 43dm$^3$ spherical explosion test apparatus was developed as an alternative to the much criticised Hartmann apparatus. It has been shown that, with the correct choice of experimental parameters, this apparatus is capable of providing explosibility data comparable with that attained in the standard 1m$^3$ apparatus.

A large scale 6.2m$^3$ explosion test facility was set up primarily for explosion suppression trials. It has been shown that, with the correct choice of experimental parameters, dust explosions with intensities comparable to those attained in the standard 1m$^3$ apparatus can be achieved. Dust explosibility determinations in this 6.2m$^3$ apparatus were highly reproducible.

Explosion hazard assessment is the quantification of the potential explosion intensity of an explosible fuel in specific industrial environments. An empirical turbulence factor, $\alpha$, is proposed to aid hazard assessment, and the Cube Law for explosibility scaling is redefined thus:

$$\left(\frac{dP}{dt}\right)_{\text{max}} \cdot V_1^{\frac{1}{3}} \cdot \frac{1}{\alpha_1} = \left(\frac{dP}{dt}\right)_{\text{max}} \cdot V_2^{\frac{1}{3}} \cdot \frac{1}{\alpha_2}$$

For turbulent gas explosion hazards $\alpha$ can assume a value $> 10$, whereas $\alpha \approx 2.0$ is typical for turbulent dust explosions.
7.2. Explosion Suppressants

7.2.1. For the explosion suppression methods considered, the evidence suggests that the predominant mechanism is physical rather than chemical.

7.2.2. The scale on which suppression of a gas explosion occurs is molecular, whereas for dust explosions the mean inter-particle separation is a critical spatial determinant for effective suppression.

7.2.3. An effective explosion suppressant must abstract rapidly sufficient heat from the combustion kernel to prevent sustained combustion and also must inert the unburned explosible fuel/air mixture.

7.2.4. It is a particular property of Halon suppressants that they can burn at elevated temperatures. Thus, if effective suppression is not achieved with Halon, the resultant 'Failed Suppression' event may be more violent than the corresponding unsuppressed explosion event.

7.2.5. If effective suppression is not achieved with water and powder suppressants, the resultant 'Failed Suppression' event will be less severe than the corresponding unsuppressed explosion event.

7.2.6. The effectiveness of a liquid suppressant is dependent on both the thermodynamics of the liquid and the physical kinetics of heat transfer and droplet vaporisation. The effectiveness of a powder suppressant is dependent on both the thermal properties of the powder and the particle size and shape distributions. The latter will influence the heat transfer rates.
7.3. **Explosion Suppressors**

7.3.1. The discharge characteristics of hemispherical suppressors have been determined experimentally. They have a very fast discharge (typically \( \approx 100 \text{ m s}^{-1} \)) but a limited throw.

7.3.2. The discharge characteristics of High Rate Discharge (HRD) suppressors have been determined experimentally for both liquid and powder suppressants. These suppressors are slower than the hemispherical suppressors (typically \( \approx 40 \text{ m s}^{-1} \)) but have a greater throw.

7.3.3. The adverse influence of peripherals (elbows, spreader type, etc) on HRD suppressor performance has been quantified.

7.3.4. A simple theory of suppressor discharge suggests that the discharge rate is proportional to the outlet area and to the square root of the propelling agent pressure. This is consistent with experimental findings.

7.3.5. Mathematical analogues of a suppressor's performance have been defined from both experiment and the simple theory. These analogues provided a basis for the mathematical model of explosion suppression.
7.4. Explosion Suppression

7.4.1. An experimental facility, based on a 6.2m³ pressure vessel, was set up and instrumented for this study. This facility was compatible with other explosion test facilities.

7.4.2. Explosion suppression experimental trials with gas and dust explosions in both 1m³ and 6.2m³ vessels, using Halon 1011, water, and powder suppressants are reported. This study has defined the efficacy and the limitations of specific explosion suppression measures.

7.4.3. Water is not an effective suppressant of gas explosions but proved very effective against explosions of the dusts evaluated.

7.4.4. The mono-ammonium phosphate based powder proved the most effective suppressant against both gas and dust explosions.

7.4.5. At the lower detection pressures, Halon 1011 proved very effective, but at the higher detection pressures this explosion suppressant could fail catastrophically to suppress the explosion.

7.4.6. More effective suppression was attained by the use of a larger number of smaller suppressors.
In general, the single exit (76mm diameter) HRD suppressor was more effective than the dual exit (19mm diameter) HRD suppressor against explosions in the 1m$^3$ apparatus.

A mathematical model of suppression system performance was developed. The validity of this model has been demonstrated by the 1m$^3$ and 6.2m$^3$ explosion suppression trials.

Explosion suppression measures against quiescent gas explosions proved less effective than theoretically predicted. It is considered that this occurs because the discharge of the suppressors significantly perturbs the predicted course of the explosion as a consequence of induced turbulence.

Comparison of theoretical predictions of suppression system performance with published results of other workers for explosion suppression trials in volumes ranging from 1m$^3$ to 20m$^3$ indicates a general correlation. In most cases the theoretical prediction errs on the side of safety.

Theoretical predictions of explosion suppression efficacy can be obtained systematically using an interactive computer program. This program is a significant design aid tool for a manufacturing company of explosion suppression systems.
8. **RECOMMENDATIONS FOR FUTURE WORK**

The work reported in this thesis has identified several aspects of explosion suppression technology which remain unexplained and has opened up a number of areas in which the limited resource has permitted only a cursory evaluation. These areas would benefit from a more detailed study. Comparable explosion and explosion suppression trials using other fuels, other suppressants, and other suppression systems would complement the results presented in this document and, thus, would establish an improved basis for the quantification of the efficacy of explosion suppression measures.

Particular aspects which, in the opinion of the author, require significant further research are listed below:

(i) compare the explosibility measurements of a wide range of industrial dusts in the $43\, \text{dm}^3$, $1\, \text{m}^3$, and $6.2\, \text{m}^3$ apparatus;

(ii) fully appraise the usefulness of the Hartmann apparatus when using a discrete ignition methodology;

(iii) seek to quantify turbulence, in as much as it affects explosion intensity, by some more absolute method to expedite more meaningful explosion hazard assessment;

(iv) study large volume gas explosions to understand the nature and causes of the artefacts reported in section 5;

(v) establish the efficacy of explosion suppression measures in large volumes ($50 - 250\, \text{m}^3$);
(vi) undertake a systematic theoretical and experimental study of the vent/suppression hybrid concept. There has been little work in this area, but the vent/suppression option can represent the only viable solution for protection of industrial plant handling very explosible dusts or plant with limited surface to fit explosion vents;

(vii) further appraise the validity and usefulness of the mathematical model of explosion suppression, both for other dusts, other suppressants, and other test volumes;

(viii) extend the concepts reported in this thesis to an appraisal of explosion suppression efficacy on the plurality of industrial plant components. In particular the following merit further study:

(i) bag filters;
(ii) large elevators;
(iii) fluidised bed driers;
(iv) spray driers;
(v) centrifuges.
The results of explosion suppression trials undertaken by other workers and available to the author are listed below. Tests with the single exit (76mm diameter) HRD explosion suppressor(s) provide additional data to test the theoretical model described in section 3.4. Computer estimates of $P_{\text{RED}}$ are included with the experimental results of these particular trials in the tables below.

**TRIAL SERIES A (237)**

<table>
<thead>
<tr>
<th>Test Volume</th>
<th>$1m^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suppression System</td>
<td>One dual exit (19mm diameter) HRD suppressor</td>
</tr>
<tr>
<td>Suppressant Concentration</td>
<td>Powder - 4kg m$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>Water - 4kg m$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>Halon 1011 - 4kg m$^{-3}$</td>
</tr>
</tbody>
</table>

**UNSUPPRESSED EXPLOSION DATA**

<table>
<thead>
<tr>
<th>FUEL</th>
<th>$t_v$ s</th>
<th>$P_{\text{max}}$ MPa</th>
<th>$K$ MPa m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Vol % $C_3H_8$</td>
<td>Quiescent</td>
<td>0.74</td>
<td>7.5</td>
</tr>
<tr>
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<td>0.88</td>
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<td>0.87</td>
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<tr>
<td>0.9</td>
<td>0.86</td>
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</tr>
<tr>
<td>1.5</td>
<td>0.85</td>
<td>20.2</td>
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</tr>
<tr>
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<td>0.78</td>
<td>7.2</td>
</tr>
<tr>
<td>Cellulose Dust</td>
<td>0.6</td>
<td>0.92</td>
<td>16.5</td>
</tr>
</tbody>
</table>

**TABLE A1**

**SUPPRESSION OF QUIESCENT $C_3H_8$/AIR - ($P_{N_2}=12$ MPa)**

<table>
<thead>
<tr>
<th>POWDER</th>
<th>WATER</th>
<th>HALON 1011</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_A$ kPa</td>
<td>$P_{\text{RED}}$ kPa</td>
<td>$P_A$ kPa</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>30</td>
<td>45</td>
<td>29</td>
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<td>50</td>
<td>75</td>
<td>47</td>
</tr>
<tr>
<td>70</td>
<td>155</td>
<td>-</td>
</tr>
</tbody>
</table>

**TABLE A2**
### SUPPRESSION OF QUIESCENT $\text{C}_3\text{H}_8$/AIR - ($P_A \sim 10\text{kPa}$)

<table>
<thead>
<tr>
<th>$P_{N2}$ (MPa)</th>
<th>$P_{\text{RED}}$ (kPa)</th>
<th>$P_{\text{RED}}$ (kPa)</th>
<th>$P_{\text{RED}}$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>300</td>
<td>630</td>
<td>1050</td>
</tr>
<tr>
<td>9</td>
<td>50</td>
<td>530</td>
<td>1090</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>520</td>
<td>1130</td>
</tr>
</tbody>
</table>

**TABLE A3**

### SUPPRESSION OF TURBULENT $\text{C}_3\text{H}_8$/AIR - ($P_A = 10\text{kPa}$, $P_{N2} = 12 \text{ MPa}$, Powder)

<table>
<thead>
<tr>
<th>$t_v$ (s)</th>
<th>$P_{\text{RED}}$ (kPa)</th>
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</thead>
<tbody>
<tr>
<td>0.3</td>
<td>680</td>
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<td>460</td>
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<tr>
<td>0.9</td>
<td>240</td>
</tr>
<tr>
<td>1.5</td>
<td>80</td>
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</table>

**TABLE A4**

### SUPPRESSION OF COAL DUST - $P_{N2} = 12 \text{ MPa}$

<table>
<thead>
<tr>
<th>$P_A$ (kPa)</th>
<th>$P_{\text{RED}}$ (kPa)</th>
<th>$P_A$ (kPa)</th>
<th>$P_{\text{RED}}$ (kPa)</th>
<th>$P_A$ (kPa)</th>
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</tr>
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<td>44</td>
<td>57</td>
<td>38</td>
<td>76</td>
<td>18</td>
<td>1140</td>
</tr>
<tr>
<td>71</td>
<td>275</td>
<td>54</td>
<td>192</td>
<td>37</td>
<td>1150</td>
</tr>
</tbody>
</table>

**TABLE A5**

### SUPPRESSION OF COAL DUST - ($P_A \sim 40\text{kPa}$)

<table>
<thead>
<tr>
<th>$P_{N2}$ (MPa)</th>
<th>$P_{\text{RED}}$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>54</td>
</tr>
<tr>
<td>9</td>
<td>62</td>
</tr>
<tr>
<td>12</td>
<td>57</td>
</tr>
</tbody>
</table>

**TABLE A6**
SUPPRESSION OF CELLULOSE DUST - \( (P_{\text{N2}} = 12 \text{ MPa}) \)

<table>
<thead>
<tr>
<th>( P_A ) kPa</th>
<th>( P_{\text{RED}} ) kPa</th>
<th>( P_A ) kPa</th>
<th>( P_{\text{RED}} ) kPa</th>
<th>( P_A ) kPa</th>
<th>( P_{\text{RED}} ) kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>27</td>
<td>1</td>
<td>80</td>
<td>4</td>
<td>85</td>
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<tr>
<td>24</td>
<td>43</td>
<td>13</td>
<td>520</td>
<td>13</td>
<td>1060</td>
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<td>37</td>
<td>153</td>
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<td>600</td>
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</tr>
<tr>
<td>54</td>
<td>510</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE A7**

SUPPRESSION OF CELLULOSE DUST - \( (P_A \sim 20 \text{kPa}) \)

<table>
<thead>
<tr>
<th>( P_{\text{N2}} ) MPa</th>
<th>( P_{\text{RED}} ) (kPa)</th>
<th>( P_{\text{RED}} ) (kPa)</th>
<th>( P_{\text{RED}} ) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>660</td>
<td>730</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>710</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>43</td>
<td>600</td>
<td>1030</td>
</tr>
</tbody>
</table>

**TABLE A8**

TRIAL SERIES B (240)

- **Test Volume**: 3.8m³
- **Suppression System**: Two single exit (76mm diameter) HRD suppressors
- **Suppressant Concentration**:
  - Powder - 4kg m⁻³
  - Water - 5.2kg m⁻³
  - Halon 1011 - 3.4kg m⁻³

UNSUPPRESSED EXPLOSION DATA

<table>
<thead>
<tr>
<th>FUEL</th>
<th>( t_v ) s</th>
<th>( P_{\text{max}} ) MPa</th>
<th>( K ) MPa m s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiescent</td>
<td>0.3</td>
<td>0.76</td>
<td>76</td>
</tr>
<tr>
<td>Coal Dust</td>
<td>0.6</td>
<td>0.82</td>
<td>11.8</td>
</tr>
<tr>
<td>Cellulose Dust</td>
<td>0.6</td>
<td>0.82</td>
<td>11.8</td>
</tr>
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**TABLE B1**
### TABLE B2

**SUPPRESSION OF QUIESCENT C<sub>3</sub>H<sub>8</sub> - P<sub>N2</sub> = 4 MPa**

<table>
<thead>
<tr>
<th>P&lt;sub&gt;A&lt;/sub&gt; (kPa)</th>
<th>P&lt;sub&gt;RED&lt;/sub&gt; (kPa)</th>
<th>P&lt;sub&gt;A&lt;/sub&gt; (kPa)</th>
<th>P&lt;sub&gt;RED&lt;/sub&gt; (kPa)</th>
<th>P&lt;sub&gt;A&lt;/sub&gt; (kPa)</th>
<th>P&lt;sub&gt;RED&lt;/sub&gt; (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experiment</td>
<td>Theory</td>
<td></td>
<td>Experiment</td>
<td>Theory</td>
</tr>
<tr>
<td>10</td>
<td>22</td>
<td>24</td>
<td>10</td>
<td>250</td>
<td>FAIL SUPPNN</td>
</tr>
<tr>
<td>30</td>
<td>54</td>
<td>62 PR</td>
<td>32</td>
<td>330</td>
<td>FAIL SUPPNN</td>
</tr>
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<td>960</td>
<td>FAIL SUPPNN</td>
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<td>&gt;200</td>
<td>FAIL SUPPNN</td>
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</table>

### TABLE B3

**SUPPRESSION OF QUIESCENT C<sub>3</sub>H<sub>8</sub>/AIR - (P<sub>A</sub> ~ 7kPa)**

<table>
<thead>
<tr>
<th>P&lt;sub&gt;N2&lt;/sub&gt; (MPa)</th>
<th>P&lt;sub&gt;RED&lt;/sub&gt; (kPa)</th>
<th>P&lt;sub&gt;RED&lt;/sub&gt; (kPa)</th>
<th>P&lt;sub&gt;RED&lt;/sub&gt; (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experiment</td>
<td>Theory</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>25</td>
<td>450</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>18</td>
<td>250</td>
</tr>
<tr>
<td>6</td>
<td>26</td>
<td>16</td>
<td>176</td>
</tr>
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### TABLE B4

**SUPPRESSION OF TURBULENT C<sub>3</sub>H<sub>8</sub>/AIR - (P<sub>A</sub> ~ 7kPa, P<sub>N2</sub> = 4 MPa)**

<table>
<thead>
<tr>
<th>t&lt;sup&gt;'&lt;/sup&gt;&lt;sup&gt;y&lt;/sup&gt; (s)</th>
<th>P&lt;sub&gt;RED&lt;/sub&gt; (kPa)</th>
<th>P&lt;sub&gt;RED&lt;/sub&gt; (kPa)</th>
<th>P&lt;sub&gt;RED&lt;/sub&gt; (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experiment</td>
<td>Theory</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>640</td>
<td>FAIL SUPPNN</td>
<td>540</td>
</tr>
<tr>
<td>0.6</td>
<td>360</td>
<td>75 PR</td>
<td>430</td>
</tr>
<tr>
<td>0.9</td>
<td>124</td>
<td>29</td>
<td>310</td>
</tr>
</tbody>
</table>

### TABLE B4
### TABLE B5

**SUPPRESSION OF COAL DUST**

<table>
<thead>
<tr>
<th>P(_A) (kPa)</th>
<th>POWDER</th>
<th>P(_A) (kPa)</th>
<th>WATER</th>
<th>P(_A) (kPa)</th>
<th>HALON 1011</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EXPERIMENT</td>
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<td>EXPERIMENT</td>
<td>THEORETICAL</td>
<td>EXPERIMENT</td>
</tr>
<tr>
<td>7</td>
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<td>11</td>
<td>7</td>
<td>21</td>
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<td>34</td>
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<td>31</td>
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</tr>
<tr>
<td>55</td>
<td>72</td>
<td>76</td>
<td>41</td>
<td>55</td>
<td>52</td>
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</table>

### TABLE B6

**SUPPRESSION OF COAL DUST**

<table>
<thead>
<tr>
<th>P(_N2) (MPa)</th>
<th>POWDER</th>
<th>P(_N2) (MPa)</th>
<th>WATER</th>
<th>P(_N2) (MPa)</th>
<th>HALON 1011</th>
</tr>
</thead>
<tbody>
<tr>
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<td>THEORETICAL</td>
<td>EXPERIMENT</td>
<td>THEORETICAL</td>
<td>EXPERIMENT</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>12</td>
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<td>-</td>
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<td>21</td>
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</table>

### TABLE B7

**SUPPRESSION OF CELLULOSE DUST**

<table>
<thead>
<tr>
<th>P(_A) (kPa)</th>
<th>POWDER</th>
<th>P(_A) (kPa)</th>
<th>WATER</th>
<th>P(_A) (kPa)</th>
<th>HALON 1011</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>34</td>
<td>110</td>
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<td>57</td>
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<tr>
<td>50</td>
<td>160</td>
<td>143 PR</td>
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### TABLE B8

**SUPPRESSION OF CELLULOSE DUST**

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<thead>
<tr>
<th>P(_N2) (MPa)</th>
<th>POWDER</th>
<th>P(_N2) (MPa)</th>
<th>WATER</th>
<th>P(_N2) (MPa)</th>
<th>HALON 1011</th>
</tr>
</thead>
<tbody>
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<td>EXPERIMENT</td>
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<td>EXPERIMENT</td>
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<td>-</td>
<td>12</td>
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<td>16</td>
</tr>
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<td>4</td>
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<td>19</td>
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<td>6</td>
<td>50</td>
<td>18</td>
<td>24</td>
<td>15</td>
<td>31</td>
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</tbody>
</table>
TRIAL SERIES C (23, 24, 104)

Test Volume: 20 m³

Suppression Systems:
(i) Dual exit (19 mm diameter) HRD suppressors
(ii) Single exit (76 mm diameter) HRD suppressors

Suppressor Charge: 4 kg mono-ammonium phosphate powder

UNSUPPRESSED EXPLOSION DATA

<table>
<thead>
<tr>
<th>FUEL</th>
<th>P_max MPa</th>
<th>K MPa m⁻¹⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5 Vol % CH₄</td>
<td>0.72</td>
<td>5.3</td>
</tr>
<tr>
<td>Coal Dust</td>
<td>0.77</td>
<td>8.5</td>
</tr>
<tr>
<td>Dextrin Dust</td>
<td>0.87</td>
<td>20.0</td>
</tr>
<tr>
<td>Pigment Dust</td>
<td>1.00</td>
<td>29.0</td>
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</table>

TABLE C1

EXPLOSION SUPPRESSION TRIALS - (P_{N₂} = 4 MPa)

<table>
<thead>
<tr>
<th>FUEL</th>
<th>NO. OF HRDs</th>
<th>P_A kPa</th>
<th>PRED (kPa)</th>
<th>PRED (kPa)</th>
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<tr>
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<td></td>
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<td>Experiment</td>
<td>Theory</td>
</tr>
<tr>
<td>9.5 Vol % CH₄</td>
<td>6</td>
<td>10</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>50</td>
<td>70</td>
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<tr>
<td></td>
<td></td>
<td>50</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Coal Dust</td>
<td>6</td>
<td>10</td>
<td>27</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>-</td>
<td>22</td>
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<td>30</td>
<td>-</td>
<td>50</td>
</tr>
<tr>
<td></td>
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<td>160</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>350</td>
<td>-</td>
</tr>
<tr>
<td>Dextrin Dust</td>
<td>8</td>
<td>10</td>
<td>92</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>-</td>
<td>100</td>
</tr>
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<td></td>
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<td>30</td>
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<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>184</td>
<td>-</td>
</tr>
<tr>
<td>Pigment Dust</td>
<td>10</td>
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<td>144</td>
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<td>240</td>
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<tr>
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<td>50</td>
<td>430</td>
<td>-</td>
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</table>

TABLE C2
TRIAL SERIES D (247)

TEST VOLUME : 1m³

SUPPRESSION SYSTEM : (i) One dual exit (19mm diameter) HRD suppressor
(ii) One single exit (76mm diameter) HRD suppressor.

SUPPRESSOR CHARGE : 4kg mono-ammonium phosphate powder

UNSUPPRESSED EXPLOSION DATA

<table>
<thead>
<tr>
<th>FUEL</th>
<th>P_max</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPa</td>
<td>MPa m s⁻¹</td>
</tr>
<tr>
<td>9.5 Vol % CH₄</td>
<td>0.71</td>
<td>5.5</td>
</tr>
<tr>
<td>4 Vol % C₃H₈</td>
<td>0.71</td>
<td>7.5</td>
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<tr>
<td>Coal Dust</td>
<td>0.85</td>
<td>8.5</td>
</tr>
<tr>
<td>Antracol Dust</td>
<td>0.86</td>
<td>20.5</td>
</tr>
<tr>
<td>Hexamethylenestraín</td>
<td>1.03</td>
<td>25.4</td>
</tr>
<tr>
<td>Pigment Dust</td>
<td>1.01</td>
<td>28.6</td>
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TABLE D1

EXPLOSION SUPPRESSION TRIALS - (one dual exit (19mm diameter) HRD, P_N2 = 6 MPa)

<table>
<thead>
<tr>
<th>P_A</th>
<th>CH₄</th>
<th>COAL</th>
<th>ANTRACOL</th>
<th>PIGMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>kPa</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
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<td>-</td>
</tr>
<tr>
<td>50</td>
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<td>105</td>
<td>340</td>
<td>-</td>
</tr>
<tr>
<td>70</td>
<td>140</td>
<td>155</td>
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<tr>
<td>100</td>
<td>230</td>
<td>230</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE D2
EXPLOSION SUPPRESSION TRIALS – (one single exit (76mm diameter) HRD, \( P_{N2} = 4 \) MPa)

<table>
<thead>
<tr>
<th>( P_A ) (kPa)</th>
<th>( \text{CH}<em>4 ) ( P</em>{\text{RED}} ) (kPa)</th>
<th>( \text{C}_3\text{H}<em>8 ) ( P</em>{\text{RED}} ) (kPa)</th>
<th>COAL ( P_{\text{RED}} ) (kPa)</th>
<th>HEXAMETHYLENETERANIN ( P_{\text{RED}} ) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>Theory</td>
<td>Experiment</td>
<td>Theory</td>
<td>Experiment</td>
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<td>110</td>
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<td>30</td>
</tr>
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<td>30</td>
<td>55</td>
<td>125</td>
<td>92</td>
<td>40</td>
</tr>
<tr>
<td>50</td>
<td>70</td>
<td>180</td>
<td>154</td>
<td>80</td>
</tr>
</tbody>
</table>

**TABLE D3**

EXPLOSION SUPPRESSION TRIALS – (one single exit (76mm diameter) HRD, \( P_{N2} = 6 \) MPa)

<table>
<thead>
<tr>
<th>( P_A ) (kPa)</th>
<th>( \text{CH}<em>4 ) ( P</em>{\text{RED}} ) (kPa)</th>
<th>( \text{HEXAMETHYLENETERANIN} ) ( P_{\text{RED}} ) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>Theory</td>
<td>Theory</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
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</tr>
<tr>
<td>50</td>
<td>65</td>
<td>215</td>
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</table>

**TABLE D4**
Calculation of the thermodynamic parameters for suppressant and for the explosion system are described.

Determination of $P_m$, $Q_m$, and $Q_o$

Examples for 70/30 CH$_4$/H$_2$ and cellulose dust are given. Note that the calculations assume no cooling, no dissociation and ideality.

15 Vol % 70/30 CH$_4$/H$_2$

<table>
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<tr>
<th></th>
<th>Initial conditions:</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_o = 0.1$ MPa, $T_o = 298$ K</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CH$_4$ 10.5 Vol % 4.3 mols m$^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H$_2$ 4.5 Vol % 1.8 mols m$^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O$_2$ 0.2 17.8 Vol % 7.3 mols m$^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>air { N$_2$ 66.3 Vol % 27.1 mols m$^{-3}$, A 0.8 Vol % 0.3 mols m$^{-3}$ }</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \quad \Delta n = 0 \quad (i) \]
\[ \text{H}_2 + \text{O}_2 \rightarrow \text{H}_2\text{O} \quad \Delta n = +\frac{1}{2} \quad (ii) \]

For completion via reactions (i) and (ii) 9.5 mols m$^{-3}$ of O$_2$ are required, but only 7.3 mols m$^{-3}$ are available.

Assume that the following reaction occurs:

\[ \text{CH}_4 + \frac{3}{2} \text{O}_2 \rightarrow \text{CO} + 2\text{H}_2\text{O} \quad \Delta n = +\frac{1}{2} \quad (iii) \]

Reaction (iii) requires 6.43 mols m$^{-3}$ of O$_2$, hence 0.67 mols m$^{-3}$ are available for combustion via reaction (ii).

Final conditions:

<table>
<thead>
<tr>
<th></th>
<th>Final conditions:</th>
</tr>
</thead>
<tbody>
<tr>
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<td>$P_m$, $T_m$</td>
</tr>
<tr>
<td></td>
<td>C0 4.3 mols m$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>H$_2$ 0.1 mols m$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>H$_2$O 10.3 mols m$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>N$_2 + A$ 27.4 mols m$^{-3}$</td>
</tr>
</tbody>
</table>

Thermodynamic data:

\[ \Delta H_f (\text{CH}_4) = -74.8 \text{ kJ mol}^{-1} \]
\[ \Delta H_f (\text{CO}) = -110.5 \text{ kJ mol}^{-1} \]
\[ \Delta H_f (\text{H}_2\text{O}) = -241.9 \text{ kJ mol}^{-1} \]

Hence \[ \Delta H_{298}^{\text{CH}_4 \rightarrow \text{CO}} = -519.7 \text{ kJ mol}^{-1} \]
\[ \Delta U = \Delta H - \Delta nRT = -520.9 \text{ kJ mol}^{-1} \]

.. Heat release via reaction (iii) is 2235 kJ m$^{-3}$

Also \[ \Delta H_{298}^{\text{H}_2 \rightarrow \text{H}_2\text{O}} = -241.9 \text{ kJ mol}^{-1} \]
\[ \Delta U = \Delta H - \Delta nRT = -243.1 \text{ kJ mol}^{-1} \]

.. Heat release via reaction (ii) is 423 kJ m$^{-3}$
Equating heat released with heat absorbed gives:

\[ 2658 = \sum \frac{n_i}{n} \Delta u_i = \sum \frac{n_i}{n_i} (H^T - H_i^{298}) = \sum \frac{n_i}{n} R (T - 298) \]

The right hand side of this expression is plotted in Figure 81. Hence, by interpolation, the maximum temperature, \( T_m = 2525 \) K.

- Maximum pressure \( P_m = \frac{2658}{298} \times \frac{42.1}{40.09} \times 0.1 = 0.874 \) MPa.

Explosion Pressure \( P_m = 0.874 \) MPa

0.75 kg m\(^{-3}\) Cellulose Dust

Initial conditions

- \( P_0 = 0.1 \) MPa, \( T_0 = 298 \) K

Cellulose

<table>
<thead>
<tr>
<th>( C_6 H_{10}O_5 )</th>
<th>705 g</th>
<th>4.4 mols m(^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_2O )</td>
<td>45</td>
<td>2.5 mols m(^{-3})</td>
</tr>
</tbody>
</table>

Air

<table>
<thead>
<tr>
<th>( O_2 )</th>
<th>21 Vol %</th>
<th>8.6 mols m(^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_2 )</td>
<td>78 Vol %</td>
<td>31.9 mols m(^{-3})</td>
</tr>
<tr>
<td>( A )</td>
<td>1 Vol %</td>
<td>0.4 mols m(^{-3})</td>
</tr>
</tbody>
</table>

\[ C_6 H_{10}O_5 + 30_2 \rightarrow 6C0 + 5 H_2O \Delta n = +8 \] (i)

There is only enough \( O_2 \) for the combustion of 2.87 mols of cellulose dust. Assume that the adsorbed \( H_2O \) is driven off, and that unburned cellulose pyrolyses by reaction (ii)

\[ C_6 H_{10}O_5 \rightarrow C_6 + 5 H_2O \Delta n = +5 \] (ii)

Final conditions

- \( P_m, T_m \)

Thermodynamic data

\[ \Delta H_f (C_6) = -110.5 \) kJ mol\(^{-1}\)
\[ \Delta H_f (H_2O) = -241.9 \) kJ mol\(^{-1}\)
\[ \Delta H_f (C_{6}H_{10}O_{5}) = -965 \) kJ mol\(^{-1}\)

Hence

\[ \Delta H_{298} C_6H_{10}O_5 \rightarrow C = -908 \) kJ mol\(^{-1}\)
\[ \Delta U = \Delta H - \Delta nRT = -923 \) kJ mol\(^{-1}\)

- Heat release via reaction (i) = 2653 kJ m\(^{-3}\)

Also

\[ \Delta H_{298} C_6H_{10}O_5 \rightarrow C = -245 \) kJ mol\(^{-1}\)
\[ \Delta U = \Delta H - \Delta nRT = -257 \) kJ mol\(^{-1}\)

- Heat release via reaction (ii) = 383 kJ m\(^{-3}\)

Total Energy Released \( Q_m = 3036 \) kJ m\(^{-3}\)

Equating heat released with heat absorbed gives:

\[ 3036 = \sum \frac{n_i}{n} \Delta u_i = \sum \frac{n_i}{n_i} (H^T - H_i^{298}) = \sum \frac{n_i}{n} R (T - 298) \]

The right hand side of this expression is plotted in Figure 81. Hence, by interpolation, the maximum temperature \( T_m = 1660 \) K.

- Maximum Pressure \( P_m = \frac{1660}{298} \times \frac{73.8}{40.9} \times 0.1 = 1.005 \) MPa.
Note that $Q_o$ for 70/30 CH$_4$/H$_2$ and Cellulose dust is given by interpolation from Figure 81 where $\alpha$ is the fuel autoignition temperature.

**Determination of $H_e$**

$H_e$ is the energy absorbed by the suppressant in increasing from its initial temperature, $T_o$, to the fuel autoignition temperature $T_e$ at constant volume, see section 3.4.

\[
H_e = \int_{T_o}^{T_e} C_1 \cdot dT + L + \int_{T_e}^{T_B} C_2 \cdot dT
\]

\[
H_{e(g)} = \int_{T_B}^{T_e} C_3 \cdot dT \quad \text{or} \quad \int_{T_o}^{T_e} C_3 \cdot dT \quad \text{if} \ T_o \geq T_B
\]

Numerical data for liquid suppressants are listed in Table 3.1. Figure 92 presents $C_g$ vs T data for the various Halons. Note that $H_e$ for water can be calculated directly from published thermodynamic data.

For powder suppressants:

\[
H_e = \int_{T_o}^{T_e} C_g \cdot dT
\]

where $C_g$ is the specific heat of the agent – see Table 6.8.
Calculation of Liquid Suppressant Vaporisation Characteristics

The droplet size distribution of suppressant discharges can be estimated from:

\[
\frac{dN}{dD} = a D^2 \exp(-bD) \tag{1}
\]

where \(dN\) is the number of droplets with diameters between \(D\) and \(D + dD\), see reference 249. The constant, \(b\), is given by:

\[
b = 5.5 \times 10^{-5} \left( \frac{Q \wedge}{\Delta P \wedge} \right)^{-\frac{1}{3}}
\]

where \(Q\) = suppressant flow (dm\(^3\) h\(^{-1}\))

\(\wedge\) = liquid surface tension

\(\wedge\) = spray discharge solid angle (radians)

\(\Delta P\) = pressure difference across nozzle

Calculated droplet size distributions for Halon 1011, Halon 1211 and water discharged from a standard single exit (75mm diameter) HRD suppressor (\(P_{\text{HRD}} = 2\) MPa) are shown in Figure 83. Both number average and weight average distributions are included. Note that the bulk of the suppressant mass is transported to the combustion zone by the relatively small number of larger droplets. Also, the median droplet size of water spray is larger than that of Halon spray discharge.

The rate of vaporisation of a liquid droplet injected into an ambient of temperature \(T\) has been derived by Marty Kanury (249). The droplet diameter \(D\) at a given time, \(t\), later is given by:

\[
D^2 = D_0^2 - \left( \frac{8 \rho_l \wedge \rho_g}{\wedge} \right) \ln \left( B + 1 \right) t \tag{2}
\]

where \(D_0\) = original diameter of droplet

\(\rho_l\) = density of liquid

\(\rho_g\) = density of gaseous medium

\(B\) = mass transfer number

\(\wedge\) = thermal diffusivity of gas, to which droplet is injected

The thermal diffusivity, \(\wedge\), is given by

\[
\wedge = \frac{k}{C_g \rho_g} \tag{3}
\]

where \(k\) = thermal conductivity of gas

\(C_g\) = specific heat of gas

The mass transfer number, \(B\), is approximately defined by:

\[
B = \frac{C_g (T - T_B)}{L + C_l (T - T_B)} \tag{4}
\]

where \(C_l\) = specific heat of liquid

\(L\) = latent heat of vaporisation

\(T_B\) = liquid boiling point

\(T_o\) = droplet initial temperature

(see Table 3.1.)
From equation (ii) the droplet evaporation time is given by:

\[ t_e = \frac{D_0^2}{6 \phi \alpha_b \gamma \ln (B+1)} \]  

Equations (ii - v) refer to droplets which are stationary in a hot quiescent gaseous medium. In explosion suppression the evaporation rate will be enhanced by forced convection since the droplets are travelling at \( 40 - 60 \, \text{m s}^{-1} \). It has been shown that the droplet diameter that will evaporate in a given time is increased by \( (1 + 0.3 \, R_e^{1/3}) \) where \( R_e \) is the Reynolds Number defined as:

\[ R_e = \frac{\nu \, D_0}{\mu} \]

where \( \nu = \) droplet velocity

\( \mu = \) kinematic viscosity of gaseous medium

Note that \( k, C_g, \alpha_g \) and \( \mu \) are functions of the ambient temperature, \( T \). Data for dry nitrogen are tabulated below:

<table>
<thead>
<tr>
<th>( T ) (^K)</th>
<th>( k_g ) ( \text{W m}^{-1} \text{K}^{-1} )</th>
<th>( C_g ) ( \text{J g}^{-1} \text{K}^{-1} )</th>
<th>( \alpha_g ) ( \text{kg m}^{-3} )</th>
<th>( \alpha_g ) ( \text{m}^2 \text{s}^{-1} )</th>
<th>( \mu ) ( \text{m}^2 \text{s}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>( 2.5 \times 10^{-2} )</td>
<td>1.03</td>
<td>1.20</td>
<td>( 2.0 \times 10^{-5} )</td>
<td>( 1.5 \times 10^{-5} )</td>
</tr>
<tr>
<td>500</td>
<td>( 3.8 \times 10^{-2} )</td>
<td>1.07</td>
<td>0.65</td>
<td>( 5.5 \times 10^{-5} )</td>
<td>( 1.4 \times 10^{-5} )</td>
</tr>
<tr>
<td>700</td>
<td>( 4.8 \times 10^{-2} )</td>
<td>1.10</td>
<td>0.46</td>
<td>( 9.6 \times 10^{-5} )</td>
<td>( 1.2 \times 10^{-5} )</td>
</tr>
<tr>
<td>1000</td>
<td>( 6.3 \times 10^{-2} )</td>
<td>1.16</td>
<td>0.32</td>
<td>( 1.7 \times 10^{-4} )</td>
<td>( 1.1 \times 10^{-5} )</td>
</tr>
<tr>
<td>1300</td>
<td>( 7.4 \times 10^{-2} )</td>
<td>1.22</td>
<td>0.25</td>
<td>( 2.4 \times 10^{-4} )</td>
<td>( 1.0 \times 10^{-5} )</td>
</tr>
<tr>
<td>1600</td>
<td>( 8.8 \times 10^{-2} )</td>
<td>1.27</td>
<td>0.20</td>
<td>( 3.5 \times 10^{-4} )</td>
<td>( 9.4 \times 10^{-4} )</td>
</tr>
<tr>
<td>1900</td>
<td>( 1.08 \times 10^{-1} )</td>
<td>1.33</td>
<td>0.17</td>
<td>( 4.8 \times 10^{-4} )</td>
<td>( 9.1 \times 10^{-4} )</td>
</tr>
<tr>
<td>2200</td>
<td>( 1.25 \times 10^{-1} )</td>
<td>1.38</td>
<td>0.15</td>
<td>( 6.0 \times 10^{-4} )</td>
<td>( 9.0 \times 10^{-4} )</td>
</tr>
<tr>
<td>2500</td>
<td>( 1.42 \times 10^{-1} )</td>
<td>1.44</td>
<td>0.13</td>
<td>( 7.6 \times 10^{-4} )</td>
<td>-</td>
</tr>
<tr>
<td>2800</td>
<td>( 1.55 \times 10^{-1} )</td>
<td>1.50</td>
<td>0.12</td>
<td>( 8.6 \times 10^{-4} )</td>
<td>-</td>
</tr>
</tbody>
</table>

Calculation of \( \gamma \)

\( \gamma \) represents the proportion of liquid phase suppressant evaporated in the unburned explosive mixture as the suppressant travels towards the fireball.

Equation (iv) is only valid for \( T > T_B \). Reference 249 defines an iterative procedure for the exact calculation of \( B \) for \( T < T_B \). Such calculations for Halon 1011, Halon 1211 and water at \( 20^\circ \text{C} \) define \( B \) values of 0.17, 0.57 and 0.005 respectively. Hence equation (ii) defines droplet evaporation in the unburned zone. Final droplet diameters of suppressant discharged into a \( 20^\circ \text{C} \) ambient at \( 40 \, \text{m s}^{-1} \) are listed below:

<table>
<thead>
<tr>
<th>Final Diameter (um)</th>
<th>Original Diameter</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halon 1011</td>
<td>42</td>
<td>95</td>
<td>197</td>
<td>293</td>
<td>398</td>
<td></td>
</tr>
<tr>
<td>Halon 1211</td>
<td>1</td>
<td>83</td>
<td>190</td>
<td>291</td>
<td>393</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>48</td>
<td>99</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>
By combining such data with the suppressant droplet size distributions the total volume of suppressant evaporated in the 10ms time interval can be estimated. Such estimates of $\phi$ are listed below for ambient temperatures of 20°C and 100°C.

<table>
<thead>
<tr>
<th></th>
<th>$T = 20^\circ C$</th>
<th>$T = 100^\circ C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halon 1011</td>
<td>3%</td>
<td>8%</td>
</tr>
<tr>
<td>Halon 1211</td>
<td>14%</td>
<td>24%</td>
</tr>
<tr>
<td>Water</td>
<td>0.2%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

Calculation of $\phi$

$\phi$ represents the proportion of liquid phase suppressant evaporated as the suppressant discharge passes through the hot combustion zone.

The droplet evaporation characteristics of Halon 1011 and water have been determined from equations (ii) above, where $B$ was defined by equation (iv), for the appropriate droplet size distributions. These calculated suppressant droplet size distributions are listed below:

<table>
<thead>
<tr>
<th>DROPLET DIAMETER</th>
<th>% of TOTAL SUPPRESSANT CHARGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu m$</td>
<td>Halon 1011</td>
</tr>
<tr>
<td>100</td>
<td>4.2</td>
</tr>
<tr>
<td>200</td>
<td>21.8</td>
</tr>
<tr>
<td>300</td>
<td>30.1</td>
</tr>
<tr>
<td>400</td>
<td>23.4</td>
</tr>
<tr>
<td>500</td>
<td>12.6</td>
</tr>
<tr>
<td>600</td>
<td>5.9</td>
</tr>
<tr>
<td>700</td>
<td>2.1</td>
</tr>
<tr>
<td>800</td>
<td>0</td>
</tr>
</tbody>
</table>

Calculation of the maximum droplet size that is completely evaporated defines the relative evaporation characteristics of Halon 1011 and water suppressant discharges, see Figures 84 and 85. Interpolation and calculation provides curves of the percentage of suppressant that will evaporate ($\phi$) as a function of combustion zone temperature for defined suppressant resident times - see Figures 86 and 87. Hence the suppressant efficiency, $\phi$, can be estimated from the appropriate curve:

$$\phi = \frac{\int_{T_e}^{T_m} \phi \, dT}{T_e}$$
Theoretical explosion and suppressant data used to calculate $P_{\text{RED}}$ using the computer model described in section 3.4. are listed below:

**FUEL: 9.5 Vol % CH$_4$**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>HALON 1011</th>
<th>HALON 1211</th>
<th>WATER</th>
<th>POWDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>K</td>
<td>760</td>
<td>844</td>
<td>844</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>kJ m$^{-3}$</td>
<td>415</td>
<td>460</td>
<td>460</td>
</tr>
<tr>
<td>$H_0$</td>
<td>J g$^{-1}$</td>
<td>445</td>
<td>428</td>
<td>3240</td>
</tr>
<tr>
<td>$H_e$ (g)</td>
<td>J g$^{-1}$</td>
<td>222</td>
<td>293</td>
<td>1003</td>
</tr>
<tr>
<td>$M_{\text{thermal}}$</td>
<td>kg m$^{-3}$</td>
<td>6.01</td>
<td>6.15</td>
<td>0.99</td>
</tr>
<tr>
<td>$\phi$ (1m$^3$)</td>
<td>%</td>
<td>90</td>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td>$\phi$ (6.2m$^3$)</td>
<td>%</td>
<td>100</td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td>$\phi$ (20m$^3$)</td>
<td>%</td>
<td>100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$M_{\text{inerting}}$ (1m$^3$)</td>
<td>kg m$^{-3}$</td>
<td>5.58</td>
<td>6.10</td>
<td>16.70</td>
</tr>
<tr>
<td>$M_{\text{inerting}}$ (6.2m$^3$)</td>
<td>kg m$^{-3}$</td>
<td>1.66</td>
<td>1.76</td>
<td>8.25</td>
</tr>
<tr>
<td>$M_{\text{inerting}}$ (20m$^3$)</td>
<td>kg m$^{-3}$</td>
<td>0.79</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**FUEL: 15 Vol % 70/30 CH$_4$/H$_2$**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>HALON 1011</th>
<th>HALON 1211</th>
<th>WATER</th>
<th>POWDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>K</td>
<td>760</td>
<td>844</td>
<td>844</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>kJ m$^{-3}$</td>
<td>415</td>
<td>460</td>
<td>460</td>
</tr>
<tr>
<td>$H_0$</td>
<td>J g$^{-1}$</td>
<td>445</td>
<td>428</td>
<td>3240</td>
</tr>
<tr>
<td>$H_e$ (g)</td>
<td>J g$^{-1}$</td>
<td>222</td>
<td>293</td>
<td>1003</td>
</tr>
<tr>
<td>$M_{\text{thermal}}$</td>
<td>kg m$^{-3}$</td>
<td>5.04</td>
<td>5.13</td>
<td>0.68</td>
</tr>
<tr>
<td>$\phi$ (1m$^3$)</td>
<td>%</td>
<td>90</td>
<td>90</td>
<td>62</td>
</tr>
<tr>
<td>$\phi$ (6.2m$^3$)</td>
<td>%</td>
<td>100</td>
<td>100</td>
<td>87</td>
</tr>
<tr>
<td>$M_{\text{inerting}}$ (1m$^3$)</td>
<td>kg m$^{-3}$</td>
<td>4.68</td>
<td>5.11</td>
<td>13.98</td>
</tr>
<tr>
<td>$M_{\text{inerting}}$ (6.2m$^3$)</td>
<td>kg m$^{-3}$</td>
<td>1.39</td>
<td>1.48</td>
<td>6.93</td>
</tr>
</tbody>
</table>
### Parameter Table

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>HALON 1011</th>
<th>HALON 1211</th>
<th>WATER</th>
<th>POWDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$</td>
<td>760</td>
<td>777</td>
<td>777</td>
<td>777</td>
</tr>
<tr>
<td>$Q_e$</td>
<td>495</td>
<td>502</td>
<td>502</td>
<td>502</td>
</tr>
<tr>
<td>$H_e$</td>
<td>445</td>
<td>410</td>
<td>3140</td>
<td>900</td>
</tr>
<tr>
<td>$H_e (g)$</td>
<td>222</td>
<td>277</td>
<td>988</td>
<td>-</td>
</tr>
<tr>
<td>$M_{thermal}$</td>
<td>6.08</td>
<td>5.74</td>
<td>0.86</td>
<td>3.00</td>
</tr>
<tr>
<td>$\phi (1m^3)$</td>
<td>90</td>
<td>90</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>$\phi (3.8m^3)$</td>
<td>100</td>
<td>100</td>
<td>85</td>
<td>100</td>
</tr>
</tbody>
</table>

- **FUEL**: 0.25 kg m$^{-3}$ Coal Dust

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>HALON 1011</th>
<th>HALON 1211</th>
<th>WATER</th>
<th>POWDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$</td>
<td>760</td>
<td>890</td>
<td>890</td>
<td>890</td>
</tr>
<tr>
<td>$Q_e$</td>
<td>500</td>
<td>650</td>
<td>650</td>
<td>650</td>
</tr>
<tr>
<td>$H_e$</td>
<td>445</td>
<td>450</td>
<td>3330</td>
<td>1080</td>
</tr>
<tr>
<td>$M_{thermal}$</td>
<td>4.83</td>
<td>4.44</td>
<td>0.60</td>
<td>1.85</td>
</tr>
<tr>
<td>$\phi$</td>
<td>90</td>
<td>90</td>
<td>52</td>
<td>100</td>
</tr>
</tbody>
</table>

- **FUEL**: 0.25 kg m$^{-3}$ Coal Dust

---

$P_m = 0.956 \text{ MPa}$

$S_u = 0.46 \text{ m s}^{-1}$

$Q_m = 3202 \text{ kJ}$

$P_m = 0.901 \text{ MPa}$

$S_u = 0.38 \text{ m s}^{-1}$

$Q_m = 2650 \text{ kJ m}^{-3}$
P_m = 1.005 MPa
S_u = 0.89 m s^{-1} (1.05 m s^{-1} for WM2)
Q_m = 3036 kJ m^{-3}

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>HALON 1011</th>
<th>HALON 1211</th>
<th>WATER</th>
<th>POWDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_e</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Q_e</td>
<td>440</td>
<td>440</td>
<td>440</td>
<td>440</td>
</tr>
<tr>
<td>H_e</td>
<td>311</td>
<td>226</td>
<td>2740</td>
<td>510</td>
</tr>
<tr>
<td>M_{thermal}</td>
<td>8.35</td>
<td>11.48</td>
<td>0.95</td>
<td>5.09</td>
</tr>
<tr>
<td>\phi (1m^3)</td>
<td>75</td>
<td>75</td>
<td>30</td>
<td>100</td>
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<tr>
<td>\phi (6.2m^3)</td>
<td>90</td>
<td>90</td>
<td>65</td>
<td>100</td>
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Droplet Vaporisation Data

<table>
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<tr>
<th>V m^3</th>
<th>\gamma ms</th>
<th>\gamma_{(HALON 1011)}</th>
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<th>\gamma_{(WATER)}</th>
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<tr>
<td>1</td>
<td>20</td>
<td>0.09</td>
<td>0.35</td>
<td>0.004</td>
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<td>3.8</td>
<td>40</td>
<td>0.14</td>
<td>0.66</td>
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<td>6.2</td>
<td>46</td>
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<td>0.64</td>
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<td>20</td>
<td>67</td>
<td>0.23</td>
<td>0.92</td>
<td>0.010</td>
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REFERENCES


6 Semenov N N; Z. Phys., 48, 571, 1928.


14 Bradley D, and Mitcheson A; Comb. & Flame, 26, 201, 1976.


16 Harris G F P; Comb. & Flame, 11, 17, 1967.


31 Metzner H, and Beck J; Berbautechnik, 18, (1), 45, 1968.
32 Klyachko L A; Pyrodynamics; 6, (19), 29, 1968.
36 Essenhigh R H, and Woodhead D W; Comb. & Flame, 2, 365, 1958.
37 Helwig N; Staub Reinhal Luft, 26, 65, 1966.
44 Bhaduri D; Comb. & Flame, 17, 15, 1971.
51 Cassel H M, and Liebman I; Comb. & Flame, 2, 467, 1959.
53 Thomas A; Shell Aviation News, 8, 14, 1953.
55 BG-Chemie; Richtlinie Nr 4 "Statische Elektrizitat", 1972.
58 Spalding D B; Fuel 30, 121, 1951.
62 Ubhayakar S K; Comb. & Flame, 26, 23, 1976.
63 Belyaev A F and Bakhman N N; Comb. Explosions and Shock Waves, 2, (4), 1, 1966.
64 Leuschke G; Staub Reinhal Luft, 26, (2), 49, 1966.
65 Health and Safety Executive; 'Dust Explosions in Factories', HMSO, 1975.
68 Leuschke G; Betriebssicherheit, 10, 365, 1967.
71 Moodie T W; ISA Trans., 10, 224, 1971.
72 Palmer K N; The Chemical Engineer, p136, March 1975.
74 O'Reilly B M; Chemistry and Industry, p24, January 1972.
76 Kuhnne G; Staub Reinhal Luft, 32, (12), , 1972.
79 Higashi T; Mining and Safety (Japan), 22, (7), 337, 1976.
81 Martin R; Powder Metallurgy, 12, (2), 70, 1976.
114 Purdue Res. Foundation; Purdue University Report 'Fire Extinguishing Agents', 1948.
115 Elkins G H J; FRS Note 327, 1957.
122 Thorne P F; FRS Note 659, 1967.
123 Thorne P F; FRS Note 1073, 1977.
135 Edmondson H, and Heap N P; Comb. & Flame, 12, 447, 1968.

Butlin R N, and Simons R F; Comb. & Flame, 12, 447, 1968.


Spence D, and McHale E T; Comb. & Flame, 24, 211, 1975.


Larsen E R; J. Fire Flammability, 1, 4, 1974.

Larsen E R; J. Fire Flammability, 2, 5, 1975.


Dewitte M, Vrebosch J, and von Tiggelen A; Comb. & Flame, 8, 257, 1964.


163 McHale E T; Comb. & Flame, 24, 277, 1975.
164 Birchall J D; Comb. & Flame, 14, 85, 1970.
166 Inami S H, and Wise H; Comb. & Flame, 2, 107, 1963.
172 British Patent No. 583 312, 1944.
174 Ministry of Supply Contract No. 6/Stores/24351/CB21(c); 1952.
179 Health and Safety at Work Act; 1974.
182 NFPA 68A; 1974.
185 Grabowski G J; NFPA Quart., 52, (2), 109, 1958.
188 Schumacher; VDSI-Schriftenreihe Heft, 6, 72, 1964.
189 Palmer K N; Chem. Ind. (Lon.), p936, 1967.
190 Grabowski G J; Fire J., 1, 21, 1968.
191 Botteri B P, and Mannheim J; Aerospace Medicine, p1180, 1969.
195 FPA; Fire Safety Sheets, FS 6015, 1974.
203 Krauchenko V S, and Yakoulev V P; Obzor Issledovanni v Oblasti Podavleniya Vzyuov Methana; Moscow 1979.
205 Scholl E W; Gluckauf-Forschungshefte S209/19; 1968.
208 Rae D, and Thompson W; Comb. & Flame, 25, 131, 1979.
210 Graviner Company Report No I/3; May 1958.
217 Peterson P; A. I. Ch. E. Petrochemical Exposistion, Houston, Texas, 1967
218 Bartknecht W; The Ladenburg Review, August 1978.
221 Fenwal Company Report No. PSR-441; 1972.
228 Scholl E W; Berggewerkschaftliche Versuchsstrecke Tgb.-Nr. 730/55/75, 197
229 Bartknecht W; Chemie-Ing Techn., 47, (6), 236, 1975.
232 Scholl E W et al., Chem-Ing Techn., 51, (1), 8, 1979

245 Bartknecht W; Private Communication, 1980.


Figure 1: Inhibition Effectiveness of various Agents

Figure 2: Inhibition Effectiveness of various Agents
FIGURE 3: Inhibition Effectiveness of various Agents

FIGURE 4: Time required for Halon 1301 Decomposition
Experimental

Theoretical

t (ms)
Pressure and Suppressant Characteristics

Suppressant delivered
slope = R₂

Suppressant required
slope = R₁

P – P₀ (MPa x 10⁻¹)

PR
0.4

PA
0

t (ms)
0 20 40 60 80 100 120

Fireball growth
Characteristic

Fireball radius (+r)
suppressant discharge characteristic

Fireball radius (-r)

Suppressor Theoretical Analogue

R (kg s⁻¹)
0 50 100

R₁

R₂

t (ms)
0 20 40 60 80

FIGURE 7: Explosion Suppression Model Nomogram
INPUT DETAILS OF EXPLOSIVE RISK

VESSEL VOLUME (CU. M)? 6.2

INITIAL AND THEORETICAL MAX. PRESSURE (BAR ABSOLUTE)? 1.06, 10.65

HOW MANY VALUES OF BURNING VELOCITY?!

VELOCITIES M/S? 0.51

IS VESSEL LOW ASPECT RATIO? N

INPUT SURFACE AREA (SQ M)? 22.3

IS EXTANT: HALON 1011 (1), WATER (2), OR POWDER (3)? 1

HOW MANY EXTINGUISHANT CONSTANTS? 1

EXTINGUISHANT CONSTANTS (KG/CU M)? 8.35

DO YOU WANT TO INPUT ADDITIONAL DATA (YES/NO)? YES

ENTER 0 IF YOU DO NOT WANT TO SPECIFY ANSWER

THROW (M)? 1.65

TDWELL3 (S)? 0

PERCENTAGE EFFICIENCY OF EXTANT.? 90

QUIESCENT GAS TURBULENCE FACTOR? 0

HOW MANY EXTINGUISHING SYSTEMS- UP TO 10? 1

INPUT DETAILS OF EACH SYSTEM

TYPE LETTER AT END OF LINE TO INDICATE-

SAME SYSTEM TO BE CONTINUED (C), OR NEXT SYSTEM (N)

SYSTEM NO. 1 DETECTION PRESSURE? 0.005

<table>
<thead>
<tr>
<th>NO.</th>
<th>CAP.</th>
<th>PRESS</th>
<th>ELBOWS</th>
<th>C OR N</th>
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<tr>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>C</td>
</tr>
</tbody>
</table>
*HEMI*

?1 : 3  : 20  : 0  : C

?1 : 3  : 20  : 1  : N

DO YOU WANT GRAPHS? YES

LONG(10), OR SHORT(25)? 10
SYSTEM No. 1

BURNING VELOCITY 0.70 M/S
EXTINGUISHANT CONSTANT 8.35 Kg/CuM
TIME STEP 0.0006 S

IN HUNDREDS

TIME (Seconds x Time step)

*=EXT REQUIRED (EST)
X=EXT REQUIRED (WORST CASE)
#=PROJECTED DELIVERY
0=INTERSECT

OVERPRESSURES (Bar)
WORST
0.41

ESTIMATE
0.28
Pressure Transducer

Explosion Chamber

Non-return Valve

Solenoid Valve

Air Reservoir

BRIDGE AMP

GALVO AMP

GALVO AMP

UV RECORDER

SEQUENCE CONTROL UNIT

IGNITION CIRCUIT

IGNITION TRIGGER

EVENT MARK

EVENT MARK

CHART DRIVE

GALVO

AMR

GALVO

AMR

BRIDGE

AMR

EUITION

TRIGGER

SEQUENCE

CONTROL

UNIT

Start

FIGURE 9: Schematic of Experimental Layout

VOLTAGE (E)

VALVE

IGNITION

FIGURE 10: Typical Explosion Pressure/time Record
FIGURE 11: Experimental Arrangement for Suppressor Discharge Tests
<table>
<thead>
<tr>
<th>ITEM No.</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>1</td>
<td>SIGHT GLASS SUPPORT</td>
</tr>
<tr>
<td>2</td>
<td>6.2m³ PRESSURE VESSEL</td>
</tr>
<tr>
<td>3</td>
<td>4 KGS SUPPRESSION BOTTLE</td>
</tr>
<tr>
<td>4</td>
<td>AUTOMATIC EXHAUST VALVE ASSY</td>
</tr>
<tr>
<td>5</td>
<td>AIR PURGE CONTROL VALVE</td>
</tr>
<tr>
<td>6</td>
<td>AIR RESERVOIR</td>
</tr>
<tr>
<td>7</td>
<td>5 LITRE DUST BOTTLE</td>
</tr>
<tr>
<td>8</td>
<td>DUST DISPERSION UNIT</td>
</tr>
<tr>
<td>9</td>
<td>DUST SPRAY RINGS</td>
</tr>
<tr>
<td>10</td>
<td>100 J ELECTRODE ASSY</td>
</tr>
<tr>
<td>11</td>
<td>GAS SPRAY ARM</td>
</tr>
<tr>
<td>12</td>
<td>AIR PURGE VALVE</td>
</tr>
<tr>
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<td>DRAINAGE VALVE</td>
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<tr>
<td>14</td>
<td>45 LITRE SPHERE</td>
</tr>
<tr>
<td>15</td>
<td>GAS CONTROL VALVE</td>
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</table>
**FIGURE 13:** Quiescent CH₄ - Air Explosions in 1m³ Vessel

**FIGURE 14:** Quiescent 70/30 CH₄/H₂ - Air Explosions in 1m³ Vessel
FIGURE 15: Cellulose dust Explosions in 1m³ Vessel

FIGURE 16: Coal dust Explosions in 1m³ Vessel
FIGURE 17: Quiescent CH₄ - Air Explosions in Hartmann Apparatus

FIGURE 18: Quiescent 9.5 Vol% CH₄ - Air Explosion P/t Records
FIGURE 19: Cellulose dust Explosions in Hartmann Apparatus

FIGURE 20: Cellulose dust Explosions in Hartmann Apparatus
FIGURE 21: Cellulose dust Explosions in Hartmann Apparatus

FIGURE 22: Cellulose dust Explosions in Hartmann Apparatus
FIGURE 23: Cellulose dust Explosions in Hartmann Apparatus

FIGURE 24: Hartmann Apparatus dust Explosibility Data
FIGURE 25: Quiescent CH$_4$ - Air Explosions in 1:1 Aspect Ratio Vertical Tube Apparatus

FIGURE 26: Quiescent 70/30 CH$_4$/H$_2$ - Air Explosions in 1:1 Aspect Ratio Vertical Tube Apparatus
FIGURE 27: Cellulose dust Explosions in 1:1 Aspect Ratio
Vertical Tube Apparatus

FIGURE 28: Cellulose dust Explosions in 1:1 Aspect Ratio
Vertical Tube Apparatus
FIGURE 29: Quiescent CH₄ - Air Explosions in 43dm³ Sphere

FIGURE 30: Quiescent 70/30 CH₄/H₂ - Air Explosions in 43dm³ Sphere
FIGURE 31: Quiescent C$_2$H$_6$ - Air Explosions in 43dm$^3$ Sphere
Quiescent 70/30 CH₄/H₂ - Air Explosion P/t Records in 43dm³ Sphere, various spark ignition energies
FIGURE 33: Cellulose dust explosions in 43dm^3 Sphere
(1.8dm^3 dispersion canister, pepper pot disperser)

P_{\text{max}} \text{(MPa)}

(\frac{dP}{dt})_{\text{max}} \text{(MPa s}^{-1}\text{)}

IGNITION: induction spark

note: each point is an average of 5 results

FIGURE 34: Cellulose dust Explosions in 43dm^3 Sphere
(0.9dm^3 dispersion canister, pepper pot disperser)
FIGURE 35: Cellulose dust Explosions in 43dm$^3$ Sphere
(Spray ring dispersion procedure)
FIGURE 36: Cellulose dust Explosions in 43m³ Sphere
(Spray rins dispersion procedure)

Note: each point is an average of 5 results
FIGURE 37: Quiescent CH₄ - Air Explosions in 6.2m³ Vessel
FIGURE 38: Quiescent 70/30 CH₄/H₂ - Air Explosions in 6.2m³ Vessel
**FIGURE 39:** Quiescent $\text{C}_3\text{H}_8$ - Air Explosions in 6.2m$^3$ Vessel
HOOP STRAIN

AXIAL STRAIN

10.2 Volume % CH₄

AXIAL WALL

RADIAL WALL

THEORETICAL CURVES

RADIAL FIREBALL GROWTH (m)

PRESSURE (MPa)

TIME (msec)

HOOP STRAIN

AXIAL STRAIN

7.6 Volume % CH₄

RADIAL FIREBALL GROWTH (m)

RADIAL WALL
FIGURE 41: Cellulose dust Explosions in 6.2m³ Vessel
FIGURE 42: Cellulose dust Explosions in 6.2m³ Vessel
FIGURE 43: Cellulose dust Explosions in Hartmann Apparatus with the addition of diluent gases
FIGURE 44: Cellulose dust Explosions in Hartmann Apparatus with the addition of diluent vapours
FIGURE 45: Cellulose dust Explosions in Hartmann Apparatus with the addition of diluent powders
FIGURE 46: Discharge Profiles of Hemispherical Suppressors
FIGURE 47: 3dm³ H2O Suppressor - depressurisation and mass discharge characteristics
FIGURE 48: Discharge Profiles of HFI Suppressors

- Powder, $P_{N_2} = 6$ MPa
- Water, $P_{N_2} = 2$ MPa
- Halon 1011, $P_{N_2} = 2$ MPa

- 30 dm$^3$ HRD
- 10 dm$^3$ HRD
- 4 dm$^3$ HRD
- 3 dm$^3$ HRD

$T$ (ms)
FIGURE 49: Influence of HRD Suppressor Fill Ratio on suppressant discharge characteristics
FIGURE 50: HRD Suppressor Canister Depressurisation Curves
FIGURE 51: Influence of HRD Suppressor propelling agent pressure on suppressant discharge characteristics
FIGURE 52: Influence of HRD Suppressor Outlet orifice area on suppressant discharge characteristics.
FIGURE 53: Suppressed Explosion Pressure/time records
FIGURE 54: 'Failed' Suppression Pressure/time records
FIGURE 55: Turbulent 9.5vol% CH₄ - air Explosions
FIGURE 56: $\frac{\Delta P}{\Delta t}_{\text{max}}$ vs $\alpha$ - Turbulent gas Explosions
FIGURE 57: Turbulence Factors, $\alpha$ and $Tu$, versus $1/t_v$
5-t

\[ t_v (1.75\text{dm}^3) \quad \bullet \quad 70/30 \text{CH}_4/\text{H}_2 (S_u = 0.49 \text{ m s}^{-1}) \]

\[ t_v (43\text{dm}^3) \]

\[ t_v (1\text{m}^3) \]

S \sim 1.25 \text{ at 'standard' } t_v \text{ in both 43dm}^3 \& 1\text{m}^3 \text{ apparatus}

**FIGURE 58:** Turbulent gas Explosions - $S_g$ Calibration Curves

\[
\begin{array}{c}
0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000 \quad 1200 \quad 1400 \\
0 \quad 2 \quad 3 \quad 4 \quad 5 \\
\end{array}
\]

\[
t_v (\text{ms})
\]

\[
t_x (\text{ms})
\]

**FIGURE 59:** Relation between preset \((t'_v)\) and actual \((t_v)\) ignition delay in Hartmann apparatus

\[
t_v (\text{ms})
\]

\[
t_v (\text{ms})
\]

\[
\text{Induction coil activation time delay}
\]
FIGURE 60: Hartmann apparatus Dust Explosibility Data

K - 1 m$^3$ apparatus
K - Hartmann apparatus

FIGURE 61: Comparison of 1 m$^3$ and Hartmann apparatus Dust Explosibility Data (Bartknecht(25))
FIGURE 62: $43\text{dm}^3$ Cellulose dust explosion P/t & P/r records
FIGURE 63: Quiescent 9.5 vol% CH$_4$ - air Explosions - Determination of burning velocity
FIGURE 64: Theoretical and Experimental Explosion P/t Curves
**FIGURE 65:** Explosion Suppression Trial P/t Record

FUEL: 0.73 kg m$^{-3}$ Cellulose dust
SUPPRESSANT: powder
SUPPRESSORS: 3 x 4dm$^3$ HRDs
IGNITION: 100J spark
DETECTION: Fault (250ms after P$_{max}$)

**FIGURE 66:** Theoretical HRD Suppressor Discharge Characteristics
FIGURE 67: Explosion Suppression Trials in 1m³ Vessel

(a) 4kg mono-ammonium phosphate

(b) 4kg Halon 1011

Fuel: 15vol% 70/30 CH₄/H₂

- PA = 50kPa
- PA = 30kPa
- PA = 10kPa
FIGURE 68: Explosion Suppression Trials in 1m³ Vessel
FIGURE 69: Explosion Suppression Trials in 1m³ Vessel

Fuel: 15vol% 70/30 CH₄/H₂
- Mono-ammonium phosphate, $P_\text{A}=10\text{kPa}$, $P_\text{N}_2=6\text{MPa}$
- Halon 1011, $P_\text{A}=5\text{kPa}$, $P_\text{N}_2=2\text{MPa}$

FIGURE 70: Explosion Suppression Trials in 1m³ Vessel

Fuel: Turbulent gas
- Mono-ammonium phosphate, $P_\text{A}=10\text{kPa}$, $P_\text{N}_2=6\text{MPa}$
- Halon 1011, $P_\text{A}=10\text{kPa}$, $P_\text{N}_2=6\text{MPa}$
FIGURE 71: Explosion Suppression Trials in 1m$^3$ Vessel
FIGURE 72: Explosion Suppression Trials in 1m³ Vessel

(a) Halon 1011 ($P_{N_2} = 2$ MPa) and mono-ammonium phosphate.

(b) Water and mono-ammonium phosphate ($P_{N_2} = 6$ MPa).

Fuel: 0.75 kg m⁻³ cellulose dust.

---

Fuel: 0.75 kg m⁻³ cellulose dust.

---
FIGURE 73: Explosion Suppression Trials in 1 m$^3$ Vessel

FUEL: 0.75 kg m$^{-3}$ Cellulose Dust

- Mono-ammonium phosphate, $P_A = 10\text{kPa}$, $P_{N_2} = 6\text{MPa}$
- Halon 1011, $P_A = 5\text{kPa}$, $P_{N_2} = 2\text{MPa}$
FIGURE 74: Explosion Suppression Trials in 6.2 m³ Vessel
SUPPRESSION: 4kg mono-ammonium phosphate powder

- x Single exit (76mm diameter) HRD suppressor, $P_{N_2} = 6$ MPa
- o Dual exit (19mm diameter) HRD suppressor, $P_{N_2} = 12$ MPa

FIGURE 75: Explosion Suppression Trials in 1m³ Vessel
FIGURE 76: Comparison between Theoretical and Experimental $P_{RED}$

$P_{RED}$ (kPa) - Computer Estimate

$P_{RED}$ (kPa) - Experimental Result

note: data extracted from Tables 5.41-5.44, 1 m$^3$ explosion suppression trials

- mono-ammonium phosphate
- water
+ Halon 1011
x Halon 1211
• quiescent gas explosions
• turbulent gas explosions
• coal dust explosions
• cellulose dust explosions

**FIGURE 77**: Comparison between Theoretical and Experimental $P_{RED}$
FIGURE 78: $P_{RED}$ vs $\alpha S_u$: Theoretical and Experimental
FIGURE 79: Influence of an induced turbulence factor on the Explosion Suppression Nomogram
FIGURE 80: Comparison between Theoretical and Experimental $P_{RED}$
FIGURE 81: Thermodynamic Properties of Test Fuels

FIGURE 82: Thermodynamic Properties of Halons
FIGURE 83: HRD Suppressor - Droplet size distributions
FIGURE 84: Evaporation of Halon 1011 Suppressant Discharge
FIGURE 85: Evaporation of Water Suppressant Discharge
FIGURE 86: Evaporation of Halon 1011 Suppressant Discharge

Efficiency $\phi = \int_{T_e}^{T_m} \frac{\dot{Q}}{T} \cdot dT$

FIGURE 87: Evaporation of Water Suppressant Discharge

Efficiency $\phi = \int_{T_e}^{T_m} \frac{\dot{Q}}{T} \cdot dT$
Characterisation of dust explosibility: comparative study of test methods

Peter Moore

The first reported work on dust explosibility testing occurred in the early part of this century and stemmed from the earlier cognition that dusts had contributed significantly to several mining disasters. Laboratory-scale test apparatuses were devised to characterise dust explosibility and have been reviewed extensively. The classification of dust explosibility as related to ignitibility in these tests and provided three categories.

- **class 1:** Dusts which ignite and propagate flame readily, the source of heat required for ignition being small.
- **class II:** Dusts which ignite readily with flame but require a larger source of ignition.
- **class III:** Dusts which do not ignite in the tests.

Recently, in the United Kingdom, a reclassification into two groups was made. Group (a): Dusts which, when tested, ignite and propagate flame in the test apparatus. Group (b): Dusts which, when tested, do not ignite and propagate flame in the test apparatus.

The most widely used test apparatus for assessing dust explosibility was developed by Hartmann. In the United Kingdom, this apparatus has been the accepted means for explosible dust hazard assessment, and hence Hartmann explosibility data have formed the basis for the design of both venting and explosion suppression safety measures. The Hartmann test method provides information on the maximum pressure, $P_{\text{max}}$, and the maximum rate of pressure rise, $(dP/dt)_{\text{max}}$, of a dust suspension ignited in a 1.23 dm³ steel cylinder. There exists in the literature a large amount of dust explosibility data from tests in the Hartmann apparatus.

Recently, the suitability of the Hartmann apparatus as a means of categorising dust explosibility has been questioned by Bartknecht. He has shown that, in the small volume of the test apparatus, a considerable underestimate of $(dP/dT)_{\text{max}}$ is obtained and that scaling of test results to larger volumes is not reliable. Bartknecht prefers the use of a 1 m³ apparatus, although this is hardly suitable for laboratory characterisation of dusts. In the absence of a better laboratory test apparatus, Burgoyne considered that the Hartmann apparatus should be retained as the means of dust explosibility measurement for the design of explosion protection measures.

Bartknecht has recently described a 20 dm³ spherical test apparatus, in which results comparable to those from a 1 m³ test vessel were obtained for a range of industrial dusts. From a study of a range of test-vessel volumes, he concluded that 20 dm³ was the smallest volume suitable for the determination of dust explosibility. Currently, consideration is being given to various standard test apparatus for the characterisation of the explosibility of industrial dusts by a working group of the International Standards Organisation.

Comparisons to date between the 1.23 dm³ Hartmann apparatus and the 1 m³ Bartknecht apparatus have tended to neglect the fact that the former uses a continuous low energy (< 10 J) ignition source, whereas the latter uses a discrete 10 kJ ignition source. Eckhoff has demonstrated that ignition delay in the Hartmann apparatus can have a marked influence on the measured explosibility, and suggested that the lower degree of turbulence that results from a long ignition delay could be one significant reason for the lower explosibility values measured using this apparatus.

Fig 1 Hartmann vertical cylinder apparatus
As well as the shape and scale of the explosion test vessel, factors such as ignition energy, ignition procedure, homogeneity of dust suspension and degree of turbulence are all known to influence the measured explosibility of a particular dust. This article assesses the influence of such factors from comparative experiments undertaken in four different test vessels. In particular the reasons for the disparity between Hartmann and 1m³ explosibility results are considered in detail.

**Test vessels**

**Standard vertical cylinder (Hartmann apparatus)**

The test apparatus, shown in Fig 1, is a 1.23dm³ explosion tube with an aspect ratio of 4.6:1. A weighed sample of the fuel dust is placed into the bottom cup and the small air reservoir (50cm³) is charged with compressed air to a pressure of 0.82MPa. A solenoid valve releases this compressed air charge, via a mushroom deflector, onto the dust, which is then dispersed upwards into the region of an ignition source. Ignition is usually achieved using either a hot coil, or a train of induction coil sparks (100Hz). The established mode of operation is that the ignition source should be initiated before the solenoid valve is activated.

**1:1 Aspect ratio cylinder**

Figure 2 shows a 1:1 aspect ratio cylinder vessel which has an internal volume of 1.75dm³ and was constructed as part of a programme to investigate the influence of aspect ratio on the measured explosion parameters in cylindrical test vessels. The explosion chamber is mounted on the standard Hartmann cup and mushroom dust dispersion system, and ignition is achieved by spark across central electrodes.

**1m³ Cylinder (Bartknecht apparatus)**

The explosion chamber (see Fig 3) has a nominal volume of 1m³ and 1:1 aspect ratio. A known weight of fuel dust is placed in a 5.4dm³ canister which is pressurised to 2MPa with compressed air. The canister is fitted with an electrically activated explosive valve which releases the dust/air mixture through a spray ring into the explosion chamber. Dust explosions are ignited using a 10kJ pyrotechnic ignition source which is detonated 0.6s after the explosive valve has been activated. This ignition delay is chosen as it takes 0.6s to disperse all of the fuel dust into the explosion chamber.

**43dm³ Sphere**

This apparatus, shown in Fig 4, was developed to provide small-scale test procedure that would produce explosibility results comparable to those obtained in the 1m³ test vessel but more conveniently and less expensively than using the latter. The dust sample is placed in a 0.9dm³ canister which is pressurised to 1.64MPa with compressed air. Dust is dispersed into the explosion chamber using either a 'pepe...
A typical pressure/time record of a quiescent gas explosion in the Hartmann vertical tube apparatus is shown in Fig 7a. From the shape of the curve, it is inferred that the growing fireball is quenched, firstly, at the combustion cylinder walls, and then at the bottom of the apparatus: the ignition electrodes are located 0.13m from the bottom of the 0.3m long cylinder. Hence a fully developed explosion does not result. The pressure/time curve of a similar explosion in the 1:1 aspect ratio cylindrical apparatus is shown in Fig 7b. Premature wall quenching does not occur in this vessel. Ideally, explosibility testing should be undertaken in a spherical apparatus with central ignition.

**Dust explosibility**

Dust explosibility is quantified in terms of the maximum explosion pressure ($P_{\text{max}}$) and the maximum rate of pressure rise ($\frac{dP}{dt}_{\text{max}}$) of the most explosible dust concentration.
The explosion pressure is essentially vessel-volume ($P$) independent, and it has been shown that $(dP/dt)_{\text{max}}$ can be scaled theoretically using the cube law relationship:

$$(dP/dt)_{\text{max}} V^{\frac{1}{3}} = K \text{(constant)}$$

$K$ is defined as the explosion rate constant - for the SI system of units it corresponds to the maximum rate of pressure rise that would result in a vessel with a volume of $1 \text{m}^3$. The explosibility parameters $P_{\text{max}}$, $(dP/dt)_{\text{max}}$ and $K$ are all influenced by changes in the initial pressure at ignition, $P_0$.

1-2dm$^3$ Versus 1m$^3$ test vessel
The measured explosibility parameters of cellulose dust ignited by induction coil sparks, 100J capacitor discharge spark and hot coil in the small cylindrical test vessels, and ignited by 10kJ pyrotechnic charge in the 1m$^3$ cylinder are compared in Table 1. All tests were undertaken using the most exploisible dust concentration (0.75-0.85kgm$^{-3}$) and preset ignition time delays. The following observations can be made:

- With induction coil spark ignition, both small test vessels show measured explosibilities some three to four times less severe than those obtained in the 1m$^3$ vessels.
- For a given ignition delay, $t_v$, 100J capacitor discharge ignition produces a more violent explosion than induction coil spark ignition.
- As previously noted, capacitor discharge ignition enables the dust to be ignited in a more turbulent condition and hence a more severe explosion is produced.
- Even with 100J capacitor discharge ignition at the optimum ignition delay, $t_v = 70 \text{ms}$, the 1:1 aspect ratio cylinder produces a measured explosibility which is still only half that recorded in the 1m$^3$ apparatus.

43dm$^3$ Versus 1m$^3$ vessels
The relationships between the explosion rate constant, $K$, in the 43dm$^3$ vessel, and the ignition delay time, $t_v$, were determined for both the ‘pepper pot’ and ‘spray ring’ dust dispersion procedures with 100J capacitor discharge ignition and are presented in Fig 8. The results at the optimum ignition delay time are shown in Table 2, together with the results of comparative tests using induction coil spark ignition. It is evident that the ‘pepper pot’ spreader dust dispersion procedure results in a less severe explosion than the spray ring dispersion procedure. It was observed that the probability of ignition diminished with reducing $t_v$ for the pepper pot dispersion method and effective ignition was not achieved for $t_v < 250 \text{ms}$, but ignition was always achieved for all $t_v > 100 \text{ms}$ with the spray ring dispersion procedure.

**Figure 8** shows that, at the optimum ignition delay (~$210 \text{ms}$) for the 43dm$^3$ spherical apparatus, the recorded explosibility, using spray ring dispersion and capacitor discharge ignition, of cellulose dust is ~20 per cent greater than that measured in the 1m$^3$ vessel. It can be inferred that, if cellulose dust with spray ring dispersion in the 43dm$^3$ spherical vessel an ignition delay of ~$265 \text{ms}$ will give results comparable to those obtained in the 1m$^3$ apparatus.

The dust dispersion methodology described for the 43dm$^3$ apparatus generates an initial overpressure in the vessel, ignition of ~$28 \text{kPa}$, which is comparable with that produced in the Hartmann apparatus. The 1m$^3$ apparatus dust dispersion procedure produces an initial overpressure of ~$14 \text{kPa}$. These overpressures and the turbulence created by the dust dispersion procedure will have an influence on the measured explosibility. Test results in the 43dm$^3$ apparatus using spray ring dispersion with a lower dust dispersion pressure, and also with partial evacuation of the explosivity chamber so that the dust explosion was initiated at atmospheric pressure, are presented in Table 3. These tests were undertaken at the optimum ignition delay of 210ms with 100J capacitive discharge ignition. They demonstrate the effect of these experimental parameters on the measured explosibility severity.

**Discussion**
Tests with two alternative ignition means have demonstrate that the nature of the ignition source can have a major influence on the severity of the explosion in a given test vessel. Differences between explosibility determinations wit

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**Table 1** Cellulose dust explosions

<table>
<thead>
<tr>
<th>Test apparatus</th>
<th>Ignition source</th>
<th>$t_v$ (ms)</th>
<th>$t_v$ (ms)</th>
<th>$P_0$ (MPa)</th>
<th>$P_{\text{max}}$ (MPa)</th>
<th>$K$ (MPa m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m$^3$</td>
<td>10kJ Pyrotechnic</td>
<td>600</td>
<td>600</td>
<td>0.014</td>
<td>0.92</td>
<td>12.3</td>
</tr>
<tr>
<td>Standard vertical tube</td>
<td>Hot coil</td>
<td>0</td>
<td>80</td>
<td>0.030</td>
<td>0.77</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>Induction spark</td>
<td>0</td>
<td>100</td>
<td>0.030</td>
<td>0.79</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>100J Capacitor spark</td>
<td>100</td>
<td>100</td>
<td>0.030</td>
<td>0.78</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>100J Capacitor spark</td>
<td>70</td>
<td>70</td>
<td>0.028</td>
<td>0.77</td>
<td>4.1</td>
</tr>
<tr>
<td>1:1 Aspect ratio vertical tube</td>
<td>Induction spark</td>
<td>0</td>
<td>100</td>
<td>0.025</td>
<td>0.77</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>100J Capacitor spark</td>
<td>100</td>
<td>100</td>
<td>0.025</td>
<td>0.83</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>100J Capacitor spark</td>
<td>70</td>
<td>70</td>
<td>0.020</td>
<td>0.83</td>
<td>6.3</td>
</tr>
</tbody>
</table>

**Table 2** Cellulose dust explosions in 0.043m$^3$ apparatus

<table>
<thead>
<tr>
<th>Dust dispersion procedure</th>
<th>Ignition source</th>
<th>$t_v$ (ms)</th>
<th>$t_v$ (ms)</th>
<th>$P_0$ (MPa)</th>
<th>$P_{\text{max}}$ (MPa)</th>
<th>$K$ (MPa m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Pepper pot’ spreader</td>
<td>Induction spark</td>
<td>0</td>
<td>285</td>
<td>0.028</td>
<td>0.93</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>100J Capacitor spark</td>
<td>250</td>
<td>250</td>
<td>0.028</td>
<td>0.95</td>
<td>9.6</td>
</tr>
<tr>
<td>Spray ring</td>
<td>Induction spark</td>
<td>0</td>
<td>460</td>
<td>0.028</td>
<td>0.96</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>100J Capacitor spark</td>
<td>210</td>
<td>210</td>
<td>0.028</td>
<td>0.98</td>
<td>14.8</td>
</tr>
</tbody>
</table>
The reported difference in cellulose dust explosibility, directly attributable to the different turbulence levels and dust cloud homogeneity, is further exaggerated in perimetal tests if the ignition delay times are not fixed. It has been shown that, for a given methodology and ignition energy, the degree of turbulence has an influence on ignition delay time. High dust-air flow rate across the ignition source can lead to a misleading evaluation of explosibility. In particular, a dust which is relatively insensitive to ignition can change some time to be effectively inert in the Hartmann tube. This time delay will mean that turbulent conditions prevailing immediately after the dust has been dispersed into the tube will have moderated considerably. Hence a less violent explosion, possibly by a factor of 10 will be recorded because of the lower turbulence prevailing at ignition. In consequence, overall, the Hartmann apparatus can give an underestimate of dust explosibility, by a factor greater than 30. This observation at the (dP/dt)_{max} values measured in the Hartmann apparatus are dependent on the ignition sensitivity of the dust determines the value of published data on dust explosibility based on Hartmann measurements. Dusts, which from ch measurements are seemingly only mildly explosive, will prove to be severely explosive.

It has been found that an explosible concentration of cellulose dust-air is in the vicinity of the electrodes in thenard vertical cylinder for some 30-40ms before ignition. Induction coil sparks occurs. The large aspect ratio of the nard vertical cylinder is a factor that contributes to the explosibility. Recorded tests in a 1:1 aspect ratio cylinder using capacitor discharge ignition, and with timum ignition delay production values closer to those tained in the 1m³ - but a considerable discrepancy still exists as the following results show.

<table>
<thead>
<tr>
<th>Dispersal procedure</th>
<th>P₀ (MPa)</th>
<th>P_{max} (MPa)</th>
<th>K (MPa m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ndard - Spray ring</td>
<td>0.82</td>
<td>0.014</td>
<td>12.8</td>
</tr>
<tr>
<td>ndard - Spray ring</td>
<td>1.64</td>
<td>0.028</td>
<td>14.8</td>
</tr>
<tr>
<td>trial evacuation - Spray ring</td>
<td>1.64</td>
<td>0</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Table 4: Explosion rate constants, using different test methods

<table>
<thead>
<tr>
<th>Dust sample</th>
<th>Hartmann apparatus</th>
<th>43dm³ Apparatus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium stearate</td>
<td>8.8</td>
<td>23.7</td>
</tr>
<tr>
<td>Phenolic resin</td>
<td>7.1</td>
<td>19.7</td>
</tr>
<tr>
<td>Cellulose</td>
<td>3.6</td>
<td>12.5</td>
</tr>
<tr>
<td>Pharmaceutical product</td>
<td>1.9</td>
<td>10.6</td>
</tr>
<tr>
<td>Gum arabic</td>
<td>1.7</td>
<td>9.0</td>
</tr>
<tr>
<td>Dried milk granules</td>
<td>0.4</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Shown that by correct choice of the experimental conditions the 43 dm³ apparatus is capable of producing experimental data comparable with those obtained in the 1m³ apparatus.

The K values determined using either the 1m³ or 43dm³ vessels have no significance in absolute terms. These test procedures represent essentially arbitrarily defined means of evaluating dust explosibility and the applicability of such data to industrial processing areas must be related to the conditions prevailing there. They tend to characterise the most severe conditions for explosibility of particular fuel/air mixtures. The actual plant the nature of the ignition source, the turbulence level and the dust cloud homogeneity are parameters which require skilled judgement and cannot be defined precisely. However, in the design of safety measures, it is important to take account of both the dust explosibility and the nature of the process to be protected. For example, the turbulence level in a microniser will be considerably greater than that in a storage silo.

To prescribe safety measures it is necessary to evaluate the explosibility of the dust at risk. The use of the standard vertical cylinder with the accepted test methodology underestimates the explosibility of dusts, and will give a misleading estimate of the hazard if the dust is somewhat insensitive to ignition. The latter difficulty could be resolved if a higher discrete energy, rather than a continuous ignition procedure was used with this apparatus. Table 4 lists comparative explosibility rate constants of various dusts, as determined from standard Hartmann apparatus measurements and from 43dm³ measurements (tₜ = 265ms.). These results serve to emphasise the limitations of the Hartmann apparatus, in particular the fact that there is no simple scaling factor.

It would be inappropriate to design explosion countermeasures for, say, a dried milk process, directly upon Hartmann data. Larger test apparatuses such as the 1m³ and 43dm³ vessels represent more suitable vessels for dust explosibility evaluations.

References
1 Faraday, M., & Lyell, C., Phil. Mag., 1845, 26
2 Ishihama, W., & Enomoto, H. J., Japan Soc. for Safety Eng., 1975, 44(4), 195
6 Health & Safety Executive, 'Dust explosions in factories', (Health and Safety at Work No 22), London: HMSO, 1975
7 Barklew, K., Forschungsbericht F45, Bundesinstitut fur Arbeitsschutz, 1971
8 Barklw, K., Staub-Reinhalt Luft, 1974, 34 (11), 381
9 Burgoyne, J. H., Chem. Ind. (London), 1978, 81
10 Barklew, K., VDI-Berichte, 1978, 304, 47
DUST EXPLOSIONS AND THEIR SUPPRESSION

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Research Division, Graviner Ltd, Colnbrook, Slough, SL3 0HA

SYNOPSIS Dust explosion countermeasures are based on an assessment of the dust explosibility. It is shown that the standard test method using the Hartmann apparatus can give unreliable results because the explosibility of a dust is dependent on its ignition sensitivity. Improved test methods are outlined. The methodology of detection and suppression of explosions with commercially available systems is described, and the results of suppression trials and comments on the advantages and disadvantages of alternative suppressants are presented. The data required for a computer aided assessment of each industrial problem, and the design of specific suppression measures, are indicated.

1. INTRODUCTION

The majority of materials handled as particulates in the agricultural, pharmaceutical, chemical, cosmetic, plastic, and food industries can, under certain conditions, explode. Therefore, the processing of these materials is potentially hazardous and plant operators are required to take necessary measures to protect both plant and personnel against the effects of such explosions.

There are two methods of countering the destructive effects of explosions. In the first, the explosion is detected very soon after its inception and sufficient suppressant delivered into the growing fireball to quench or suppress it before significant pressure is developed in the plant. In the second, the explosion is vented into the surrounding environment by rupturing a weak vent panel in the plant, thus relieving the pressure and preventing plant damage. Figure 1 shows a vented propane/air explosion. The immediate effect is a 10m jet of flame and a noise heard over a very large area. With vented dust explosions an additional hazard could be the dispersion of toxic combustion products. Venting countermeasures therefore necessitate a large 'safe area' surrounding each vent panel.

The application of both explosion suppression and explosion venting techniques requires a meaningful estimate of the violence of the severest explosion that is possible in the industrial plant processing a particular material. This enables the necessary explosion countermeasures to be designed and hence forms a most important part of explosion suppression technology.

2. EXPLOSIBILITY ASSESSMENT

The explosibility of a fuel is usually described in terms of the maximum pressure, \( P_{max} \), and the maximum rate of pressure rise, \( (\frac{dP}{dt})_{max} \), as measured in an experimental test vessel, for the most explosive concentration of the particular fuel. The maximum pressure is essentially vessel volume independent, whereas the maximum rate of pressure rise is a function of vessel volume. Maisey (Ref. 1) identified a cube law relation between \( (\frac{dP}{dt})_{max} \) and volume, \( V \):

\[
(\frac{dP}{dt})_{max} \propto V = K
\]

where \( K \) is the explosibility rate constant. From a measurement of the time, \( t \), required to reach a certain pressure in a specific volume, \( V \), the time, \( t_{x} \), required to attain the same pressure in a volume, \( V_{x} \), is given by:

\[
t_{x} = \frac{V}{V_{x}}t
\]

In reality it is not possible to achieve a quiescent dust/air suspension, and the turbulence of a dust/air suspension increases the explosion severity. Since turbulence levels vary from vessel to vessel, equation (1) needs to be amended to:

\[
(\frac{dP}{dt})_{max} \propto V = \alpha \cdot K
\]

where \( K_{\alpha} \) is the explosibility rate constant specified to the fuel in a quiescent state and \( \alpha \) is the turbulence factor.

Figure 2 shows the measured \( (\frac{dP}{dt})_{max} \) values of gas explosions in a 1m³ vessel for various degrees of turbulence. A highly turbulent fuel can explode with ten times the severity of the corresponding quiescent fuel. Since it is not possible to measure the explosibility of a quiescent dust, a precise determination of the turbulence factor of an experimental dust explosion is not possible. In practice, a turbulence factor of 4.5 is considered to represent the highest level of turbulence encountered in industrial processing and turbulence factors of 2-3 are common for most industrial environments.
The current UK procedure for the design of safety measures to give protection against the effects of explosions requires that the dust at risk should be evaluated in the standard Hartmann vertical tube apparatus (Ref. 2). In the Hartmann apparatus, the dust is dispersed into a 1.23dm$^3$ explosion tube onto a continuous ignition source, which is typically a hot coil or a train of induction coil sparks, and $(dP/dt)_{max}$ and $(dP/dt)_{max}$ are measured from the recorded explosion pressure/time history. High-speed photography has shown that a considerable delay occurs between the arrival of an explosive dust cloud at the ignition source and the effective initiation of the explosion. Eckhoff (Ref. 3) has demonstrated that the measured explosibility of lycopodium spores decreases with increasing ignition delay in the Hartmann apparatus. Figure 3 shows similar behaviour for cellulose dust. The longer the delay between dust dispersion and ignition, the lower is the resultant turbulence at ignition, and hence the lower is the recorded explosibility of the dust.

Tests with alternative ignition procedures in various test apparatus have identified a relation between ignition delay and turbulence level. It is concluded that Hartmann test data are subject to certain inconsistencies, since the recorded dust explosibility is dependent on its ignition sensitivity. This occurs because the standard test methodology does not control the ignition delay time. Ignition delay times were estimated from the pressure/time records of over 100 dusts that have been evaluated in the Hartmann apparatus over the last 3 years. The results, presented as a plot of ignition delay time, $t_i$, against measured explosibility, $(dP/dt)_{max}$, are shown in Figure 4. Most dusts with $(dP/dt)_{max}$ values less than 5 MPa s$^{-1}$ have extended ignition delay times. Hence these measurements are not meaningful assessments of the potential explosive violence of these fuels. Bartknecht (Ref. 4) has also shown that this test method can result in a considerable underestimate of the dust explosibility, and that scaling to large volumes is not directly applicable.

2.2 Progress towards a reliable standard

It must be accepted that the Hartmann apparatus, using the current test methodology, does not give reliable dust explosibility data. Hence venting and explosion suppression countermeasures should not be designed with reference to such data. Results published by Bartknecht have demonstrated that dust explosibility measured in the Hartmann apparatus is generally some 2.5 times less severe than the corresponding measurement in larger volume apparatus, in this case $>1$m$^3$ (see Figure 5). The difference, however, becomes more pronounced for the dusts that are less violently explosive. The similarity between Figures 4 and 5 is evident.

This whole question of hazard assessment is being reviewed by a working group (ISO/TC21/SC5/WG3) of the International Standards Organisation. The current philosophy of the working group is to accept a 1m$^3$ apparatus as a reference apparatus. Other types of test apparatus must be shown to give dust explosibility determinations which can be related to the 1m$^3$ measurements, over the complete range of explosibilities. Bartknecht (Ref. 5) has recently described a new spherical apparatus, and the author currently uses a 43m$^3$ spherical apparatus for dust explosibility measurements necessary for the design of explosion suppression measures. Both of these vessels give results consistent with the 1m$^3$ vessel, and are very much easier and cheaper to operate.

3. EXPLOSION SUPPRESSION SYSTEMS

3.1 Detectors and suppressors

Explosion suppression as an alternative to venting was developed by Grawner Ltd. in the 1950's. A range of hardware was evolved and this has been progressively expanded and improved to enable suppression systems to be offered for a wide range of industrial applications.

Figure 6 shows the pressure/time history during the early stages of a typical developing explosion, and demonstrates the operational characteristics of an explosion suppression system. Most industrial plant is only capable of withstanding pressures of 0.02-0.03 MPa; hence the time available to suppress the explosion, i.e. keep the overpressure to $\leq 0.02$ MPa, is typically only a few tens of milliseconds.

Explosions are detected using either a pressure threshold detector or a rate-of-rise pressure detector. Typically such detectors activate at settings of 0.0035MPa and 0.08MPa s$^{-1}$ respectively. The rate-of-rise pressure detector has an upper pressure threshold setting to ensure that 'slow' explosions are also identified. This detector is used in preference to the threshold detector to reduce the probability of false activations in industrial plants where the operating pressure is somewhat variable. It also has a superior performance to the threshold detector in small volume installations.

Explosion suppressors which have suppressant capacities ranging from 0.5 to 30 dm$^3$ are available to the engineer designing an explosion suppression system. A hemispherical type suppressor is shown in Figure 7a. It consists of a scored hemispherical casing which contains liquid suppressant. Hydraulic shock, generated by an electrically fired detonator located in the suppressant, 'petals' the fragile dome and releases the suppressant into the plant. This type of suppressor is exceptionally fast, delivering suppressant into the explosion within 5ms at an initial discharge velocity in excess of 200ms$^{-1}$; but it has a limited discharge range. It is particularly suited to the smaller installations where pressure rises are very rapid. It is installed inside the plant. A high rate discharge suppressor is shown in Figure 7b. This type of suppressor is used in the larger installations where more time is available for suppression, but a greater suppressant throw is required. These suppressors contain either liquid or gaseous suppressant which is stored under a high pressure of nitrogen. They are mounted on the outside of the plant. A fragile disc is explosively ruptured and the suppressant is dispersed into the plant with a velocity of some 30ms$^{-1}$ and a
mass discharge rate in excess of 100kg s\(^{-1}\) which is sustained until at least 50% of the contents are discharged. The first of the suppressant reaches the plant within 10-15ms of the system activation.

A central control unit provides continuous monitoring of external circuits and initiates automatic plant shut-down in the event of system activation. Explosion suppression measures can incorporate high speed isolation valves and advanced inverting measures to prevent flame propagation down interconnecting ducting, thus ensuring that the explosion cannot propagate to other parts of the plant. Figure 8 shows a typical Graviner explosion suppression installation.

3.2 Testing suppression equipment

The effectiveness of explosion suppression measures are determined by comprehensive evaluation of the limits of a system's performance in special large volume vessels capable of withstanding the unsuppressed explosion overpressure. As part of an international study, trials were recently carried out, in collaboration with Dr E.W. Scholl, using a 1m\(^3\) test vessel at Bergbau Versuchsstrecke, Dortmund. The main aim of these trials was to evaluate the performance of a single 75mm diameter outlet high-rate discharge system containing either chlorobromomethane (Halon 1011), water, or ammonium phosphate powder.

Tests were undertaken using both gas and dust explosions, and a range of detection pressures extending up to 0.05MPa, which is more than ten times the detection pressure used in most industrial applications. Resultant suppressed explosion overpressures against 15 vol % 70/30 CH\(_4\)/H\(_2\) explosions (K = 9.5MPa m s\(^{-1}\)) and 2.75kg m\(^{-3}\) cellulose dust explosions (K = 12.5MPa m s\(^{-1}\)) are presented in Figure 9. In these tests the suppressant propelling agent pressure was 6MPa. It is evident that water is not an effective suppressant of gas explosions, and that Halon 1011 is under these test conditions more effective at the higher detection pressure. Figure 10 shows the results of trials with two systems:

(i) Halon 1011, Detection pressure = 0.05MPa, propelling agent pressure = 2MPa.

(ii) Ammonium Phosphate power, Detection pressure = 0.01MPa, Propelling agent pressure = 6MPa.

with various suppressant concentrations against turbulent cellulose dust explosions. These results indicate the minimum suppressant concentrations under these test conditions.

3.3 Specific system design

The testing of explosion suppression measures in a particular volume obviously generates valuable information which is relevant to industrial hazards in similar volumes. Translation of this information to larger and smaller volumes, however, is not a simple matter. The problems of such scaling are illustrated below.

Consider the suppression of turbulent cellulose dust explosions in spherical vessels of 1m, 1.5m and 2m diameters respectively, using a single 75mm diameter outlet high-rate discharge suppressor of suitable capacity such that the final suppressant concentration in each vessel is 4kg m\(^{-3}\).

Figure 11 shows the suppressant discharge characteristic of a typical 75mm high-rate discharge system. The times required to completely distribute the suppressant in each of the vessels are 34, 50 and 76ms respectively.

Figure 12 shows the pressure/time histories of unsuppressed cellulose dust explosions in each of the vessels. For a predetermined detection pressure P\(_d\) = 0.0035MPa, superimposition of the relevant discharge time enables the suppressed explosion overpressure, P\(_{red}\), to be deduced. Figure 12 shows that this specific suppression system is more effective in the intermediate volume vessel. In the case of the 1m diameter vessel the suppression system inertia limits its performance. More effective suppression would be achieved with the faster acting hemispherical suppressors. In the case of the 2m diameter vessel the extinguishant throw limits the system performance. More effective suppression would be achieved using either several suppressors or a very high-rate discharge suppressor.

This analysis is, of course, a gross oversimplification of the way in which the capability of explosion suppression measures are assessed. Graviner explosion suppression systems are designed with the aid of computer simulation techniques which take account of suppressant dispersion, concentration, droplet/particle size, evaporation rate, and mode of action, as well as the relevant parameters of the exploisible material and the industrial environment.

Many factors have to be considered in choosing a suppressant. Water appears attractive because it is inexpensive, but as it is only about half as dense as halons or powders and as the mass of suppressant is a most important factor, twice as much has to be used. This can mean twice the number of discharge suppressors. For outside installations, in particular, water must contain a suitable antifreeze.

Halon suppressants have general applicability, but cannot be used where high detection pressures are necessary because of very variable plant operating pressures. They are the only suppressants which can be used where it would be costly or undesirable to contaminate plant or product, as they are chemically pure and very volatile. Thus, the plant can be restarted a short time after a suppression event. This is particularly important in the pharmaceutical and food processing industries.

Powder suppressants are useful where high detection pressures have to be used, and where the dust is very violently exploisible. In general, their use results in overpressures greater than the 0.03MPa which Halons can achieve, and therefore the plant must be correspondingly stronger.
4. CONCLUSIONS

It has been shown that the standard Hartmann apparatus can give unreliable dust explosibility data because the experimental procedure does not control the ignition delay time. Improved apparatus and methods are now available and should be used for the design of explosion protection measures.

The following basic information is required to assist in the design of explosion suppression systems:

   a) a meaningful assessment of the explosibility of the fuel;
   b) the performance characteristics of explosion suppression hardware, and
   c) the geometry, turbulence level and operating characteristics of the processing area at risk.

Computer simulation techniques are used to design the optimum explosion suppression system for the particular industrial hazard.

REFERENCES


Fig. 1  Vented propane/air explosion. (25m³ test apparatus situated in an airship hanger) Photograph by courtesy of Fire Research Station, Borehamwood

Fig. 2  Turbulent gas explosion tests in a 1m³ vessel

Fig. 3  Influence of ignition delay time on the measured explosibility of cellulose dust in the Hartmann apparatus

Fig. 4  The measured ignition delay and maximum rate of pressure rise for various dusts tested in the Hartmann apparatus

Fig. 5  Relation between dust explosibility measurements in the Hartmann apparatus and in a large apparatus (4)

Fig. 6  Comparison of pressure/time histories of unsuppressed and suppressed explosions
Fig. 7  a  Hemispherical explosion suppressor  
   b  High rate discharge explosion suppressor

Fig. 8  Explosion suppression equipment installed on a cyclone dust collection system
Fig. 9 Results of explosion suppression trials with alternative suppressants against

a) 70/30 CH₄/H₂ gas explosions
b) cellulose dust explosions

Fig. 10 Results of cellulose dust explosion suppression trials using various suppressant concentrations

Fig. 11 Suppressant discharge characteristic of a 75mm diameter outlet high rate discharge explosion suppressor

Fig. 12 Estimation of suppressed explosion overpressures for turbulent cellulose dust explosions in 1m, 1.5m and 2m diameter vessels using a particular suppression system
DUST EXPLOSION HAZARD ASSESSMENT

P.E. Moore

Measurement of dust explosibility in the Hartmann apparatus is known to be unreliable. It is shown that this arises because the Hartmann test method uses a continuous, rather than a discrete ignition procedure.

The problem of turbulence, within the context of hazard assessment, is discussed and the inclusion of a turbulence factor within the cube law proposed.

INTRODUCTION

It is well known that dusts, when dispersed as a cloud, can explode. The quantification of the severity of explosion that is likely with a particular dust is of vital importance to the constructors of industrial plant, the designers of explosion protection measures, and to the user industries. In the United Kingdom the Hartmann vertical tube apparatus is used extensively for this purpose. However, it has been shown experimentally (1, 2) that this test procedure can severely underestimate explosibility parameters, and that there is no simple correlation between results obtained in this, and large volume (> 1 m³) test apparatus.

Active explosion protection measures, such as venting and explosion suppression, must be designed such that their operational effectiveness can be assured. The work described below arose out of the necessity to make explosion protection measures more cost effective than those based on an unquestioned dependence on a Hartmann apparatus assessment of the hazard. This article investigates the limitations of the Hartmann apparatus test procedure, discusses alternative test methods and the applicability of such test results to the industrial environment. In particular, the importance of turbulence on the growth of an explosion is discussed.

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are summarized in Table 2. It is evident that the resultant explosibility ratios are fairly similar, although the range of 
(dp/dt)\text{max} values varies from 27 to 143 MPa s\(^{-1}\). Furthermore, a reasonable correspondence between gas and dust explosibility test results is evident. These results suggest that:

1) the influence of turbulence on dust explosibility is, to a first approximation, independent of the absolute explosibility of the material.

11) absolute turbulence of a particular dust dispersion procedure may be estimated by comparable explosion tests with quiescent and turbulent gas, where the turbulence level is defined as the ratio: (dp/dt)\text{max} - turbulent

\[(dp/dt)\text{max} - \text{quiescent}

Nagy (9) has shown experimentally and theoretically that both \(P_0\) and (dp/dt)\text{max} measurements are proportional to the initial pressure, \(P_0\). To quantify the influence of turbulence using comparable gas explosion test procedures, a turbulence factor, \(\alpha\), must be defined:

\[\alpha = \frac{(dp/dt)\text{max}}{(dp/dt)\text{max}-\text{quiescent}}\]

Limited data for the 1 m\(^3\) and 43 dm\(^3\) test procedures are summarised in Figure 7. It is apparent that at the standard ignition delay times of 265 and 600 ms for the 43 dm\(^3\) test procedures used in the 1 m\(^3\) and 4 m\(^3\) vessels respectively, similar levels of turbulence prevail.

To account for turbulence differences which occur, the cube law should be restated as:

\[(dp/dt)\text{max} = \alpha V^\frac{3}{2} \]

where \(\alpha\) is the explosion rate constant specific to the fuel in a quiescent state (a theoretical parameter) and \(V\) is the turbulence level corresponding to the test condition or the industrial environment.

**HAZARD ASSESSMENT**

Explosion hazard quantification of combustible dusts, and of flammable gases, in industrial applications is a pre-requisite to the design of suitable explosion countermeasures. The severity of the hazard is dependent on the conditions prevailing in normal and abnormal working within the industrial plant. In particular, turbulence and air flow levels within a plant processing segment can have a major influence on the resultant explosion severity. In standard test equipment, such as the Barkmann 1 m\(^3\) apparatus, a specific turbulence level for dust explosibility measurement is applied. Such an explosibility determination may represent an underestimate, or an overestimate, of the explosion severity likely in an industrial application. Hence an explosibility determination given as a measure of the explosibility of the combustible material dispersed as a cloud in air, but does not quantify the actual hazard per se.
REFERENCES

Figure 1 Hartmann vertical tube apparatus.

Figure 2 Comparison of Hartmann and large volume dust explosibility data - reference 1.
BUREAU D'ETUDE & CENTRE DE VENTE
POUR LA PROTECTION
CONTRE LES RISQUES D'EXPLOSIONS

SYMPATHY

PROTECTION PRATIQUE
CONTRE LES EXPLOSIONS

1ÈRE PARTIE: PROTECTION CONTRE LES
EXPLOSIONS DE GAZ
2ÈME PARTIE: PROTECTION CONTRE LES
EXPLOSIONS DE POUSSIÈRES

L'inscription est possible pour chaque partie séparément.

Symposium où toute l'information disponible sur la protection contre les risques d'explosions sera confrontée à la situation pratique

DESIGNING EXPLOSION SUPPRESSION MEASURES FOR INDUSTRY

P. E. MOORE
Principal Research Scientist at GRAVNER Ltd.
The first philosophy leads to certain generalisations about suppression system design and plant requirement. The limits of effectiveness of specific explosion suppression systems are well documented. For example, it can be stated that explosion suppression systems based on ammonium phosphate powder suppressors will be effective providing that the following conditions apply:

(i) The measured dust explosibility gives KC200 bar
m s⁻¹
(ii) The particulate material is not metallic
(iii) The system detection pressure pₛ<0.1 bar
(iv) Suppressors are deployed to attain effective suppressant dispersion within 100 ms
(v) The final suppressant concentration is >3kg m⁻³
(viii) The plant is shock resistant to a pressure pulse of 1 bar

This first philosophy defines an unambiguous limit of a suppression system's capability - but gives no direct measure of system flexibility within these somewhat arbitrary boundaries. For example, the use of a low detection pressure threshold, or an appropriate radiation detector, will result in a very low suppression pressure - hence the requirement that the plant should be strengthened to withstand 1 bar may be unnecessarily stringent. Similarly, fitment of the "standard" suppression system to a plant which is processing dust with a known K value of 5<50 bar m s⁻¹ implies that the suppression system is oversized and the plant operator is required to meet the unnecessary cost of such over-designing. Such economic considerations are particularly pertinent for large volume considerations.

The alternative philosophy introduces a measure of flexibility; but this must be coupled with limits of safety. In practice, a lot of industrial plant is unable to withstand a pressure pulse of 1 bar without recourse to some plant strengthening. Explosion suppression measures can be designed to restrict pressure build up to below 0.25 bar. Such a system requires both very fast suppressors and low detection pressure settings, with their attendant increased risk of false activation. The influence of suppression system hardware, the choice of suppressant, and the type of detection all affect the performance capability of an explosion suppression system. These aspects, and the conditions necessary for the design of explosion suppression measures are discussed below.

Cont .... /4

EXPLOSION SUPPRESSION HARDWARE

Radiation detection is the most effective, and is the preferred choice for solvent vapour and gaseous explosion hazards (7). For dust explosions, a pressure detector is the usual choice of detection because radiation from the fireball may be obscured by the dust cloud. Threshold pressure detectors are manufactured by Graviner with pressure settings in the range 0.02-0.3 bar. These detectors - see figure 2 - are of robust design and use a large pressure sensitive membrane. Their response time and pressure activation pressures are not significantly affected by accumulations of dust on the diaphragm. In certain circumstances, a 'rate of rise' detector is chosen. This type of detector is useful in small plant where the normal pressure fluctuations may temporarily exceed the threshold level for which activation is required.

The selection of the appropriate type of explosion suppressor (a) for a specific application is an important part of explosion suppression technology. Hemispherical suppressors have a negligible response time and can thrust liquid suppressant into the plant at near supersonic velocities - but they have a limited throw. They are mounted inside the plant and are not suited to high temperature process applications. High rate discharge (HRD) suppressors are available in capacities ranging from 4-70kg. The following outlet sizes are currently marketed by Graviner:

(i) 75mm diameter single outlet
(ii) 19mm diameter single outlet
(iii) 30mm diameter single outlet
(iv) 19mm diameter double outlet

Liquid or powder suppressant is contained in a container under a high pressure (20-120 bar) of nitrogen. This type of suppressor has a 5-10ms response time and delivers suppressant at ~ 30m s⁻¹. The larger diameter outlet HRD have superior suppressant mass discharge characteristics. The suppressant discharge velocity is increased by the use of higher propelling agent pressures. Three of the range of explosion suppressors are shown in figure 3.

The choice of suppressant may be influenced by the type of explosive dust, and by the type of industrial process. In general, ammonium phosphate powder is the most effective suppressant against most explosible dusts. However, liq

Cont ....../5
Cont.

"The system was designed to provide a simple and effective way of comparing and contrasting the effectiveness of different presentation methods. By comparing the effects of various methods on audience perception, the researchers aimed to identify the most effective approaches for delivering educational content. The study involved presenting the same material using different methods and assessing the audience's understanding and retention of the content. The results indicated that interactive presentations, such as those involving multimedia elements, were generally more effective than traditional lectures or slideshows. However, the effectiveness of a presentation method also depended on the subject matter and the audience's background knowledge. The findings have implications for both educators and learners, suggesting that a combination of methods may be the most effective approach for different types of content and audiences."

**SYSTEM DESIGN**

The system was designed to provide a simple and effective way of comparing and contrasting the effectiveness of different presentation methods. By comparing the effects of various methods on audience perception, the researchers aimed to identify the most effective approaches for delivering educational content. The study involved presenting the same material using different methods and assessing the audience's understanding and retention of the content. The results indicated that interactive presentations, such as those involving multimedia elements, were generally more effective than traditional lectures or slideshows. However, the effectiveness of a presentation method also depended on the subject matter and the audience's background knowledge. The findings have implications for both educators and learners, suggesting that a combination of methods may be the most effective approach for different types of content and audiences.
A 'failed suppression' will be predicted if the suppressant is delivered too slowly, or if insufficient suppressant is delivered. These three modes of failure are illustrated in Figure 7. The concept 'failed suppression' implies that the combustion wave continues to the vessel extremity. In the case of water and powder suppressants the resultant overpressures will be somewhat lower than the measured unsuppressed explosion pressure because they will partially quench the growing fireball; whereas with halons the final pressure may be slightly higher than the measured unsuppressed explosion pressure because halons will pyrolyse (8) at such high temperatures and pressures.

Figures 8 and 9 demonstrate the validity of this mathematical simulation procedure for halon, water and powder suppressants against gas and dust explosions in a 1m$^3$ vessel. With few exceptions, the model predicts a higher maximum explosion pressure than is measured. In all reported experiments, both published and 'in house', where a 'failed suppression' was measured experimentally, the model has predicted 'failed suppression'. Occasionally the model has predicted 'failed suppression' when experiment has indicated that a measure of suppression is possible. Figures 10, 11, compare measured suppressed explosion pressures with theoretical predictions for halon and powder suppression systems against turbulent gas explosions of increasing severity. Note that the models prediction of failure err on the side of safety. These data also serve to emphasize the greater effectiveness of powder suppressant against this type of risk. Such a mathematical tool provides a greater degree of flexibility to suppression system design.

In industrial practice a suppression system designed using this mathematical model would only be installed provided that certain safety factors are met. In particular:

(i) the suppressant delivery rate, at suppression, must exceed the suppressant requirement rate by a factor greater than 2.

(ii) the mass of suppressant delivered must exceed the mass of suppressant required by at least 50%.

Detailed applications design, which ensures that detectors and suppressors are effectively deployed and such processing parameters as high and low product levels are taken into account; coupled with theoretical simulations of suppression system performance provides a tailor made suppression system for each application. In practice, this mathematical tool is the basis of an interactive computer program.

Hence explosion suppression systems can be custom designed to achieve most effective suppression (i.e. lowest suppressed explosion pressures), or to be most cost effective as appropriate. Dynamic or periodic use of computer technology enables protection for each and every suppression system installation to be carefully validated, despite the complexities of the physics and chemistry associated with explosion suppression technology and the vast range of plant processing conditions.

An example of Industrial Application.

In practice, explosion protection can be provided by containment, inerting, venting or suppression and it is not unusual to choose appropriate combinations of these protection measures to provide complete plant protection. Figure 12 shows a hypothetical dust processing plant segment which has been chosen to illustrate the practical application of explosion suppression measures. The example is purely illustrative, and it must not be inferred that the protection measures described are necessarily the most appropriate for other similar types of industrial plant.

The explosion suppression system has been divided into discrete zones. Detection of an incipient explosion within any one zone will activate the explosion suppressors etc. associated with that zone, and will initiate automatic plant shut down. Suppressors in adjacent zones will not be operated unless the explosion propagates into these zones. Zone boundaries are chosen to minimise the likelihood of flame and explosion propagation into adjacent plant segments. The system is designed to reduce cost and plant 'down time' arising from an event, or a spurious activation. Furthermore it aids the location and identification of the cause of the explosion wherever possible.

It will be noted from Figure 12 that pressure detectors have been sited in pairs throughout the plant. Both of these detectors are required to respond to activate the suppressors in that zone. This minimises false activation arising from spurious shock or vibration effects. However, zones fitted with more than one pair of detector will have their suppressors activated when any one pair responds to an incipient explosion. Pairs of detectors are located to provide complete plant protection.

Cont........./8
REFERENCES

1) Bartknecht W, 1971, Staub-Reinhalt Luft 31 (3) 28
2) Moore P E, 1980, Inst Chem Eng Sym Ser No 58
   "Chemical Process Hazards VII" p 77
3) Moore P E, 1979, Chem Ind (London) 430
4) Bartknecht W, 1978 VDI Berichte 34 47
5) VDI 3676 June 1979
6) Maisey HR, 1980, Inst Chem Eng Sym Ser No 58
   "Chemical Process Hazards VII" p 171
8) Purlee H E et. al; 1966 US Bur Mines RI 6748

FIGURES

Figure 1. Hartmann Apparatus
Figure 2. Explosion pressure threshold detector
Figure 3. Explosion Suppressors
   a) Hemispherical suppressor
   b) 75mm outlet HRD suppressor
   c) 75mm outlet HRD suppressor
   powder suppressant
Figure 4. Results of cellulose dust explosion
   suppression trials using conventionally
   marketed halon and powder systems
Figure 5. Comparison of Experimental and Theoretical
   Explosion P vs t curves.
Figure 6. Suppression system performance criteria
Figure 7. 'Failed Suppression' criteria
Figure 8. Comparison of measured and predicted
   suppressed explosion pressures - three
   fuels (various suppression systems)
Figure 9. Comparison of measured and predicted
   suppressed explosion pressures - three
   suppressants (various fuels)
Figure 10. Comparison of measured and predicted
   suppressed explosion pressures - halon 1011
   against turbulent gas explosions
Figure 11. Comparison of measured and predicted
   suppressed explosion pressures - ammonium
   phosphate powder against turbulent gas
   explosions.
Figure 12. Explosion suppression measures for a
   hypothetical processing plant.
SUPPRESSION EFFICIENCY

MASS OF SUPPRESSANT

REQUIRED

DELIVERED

a) RELIABLE SUPPRESSION

REQUIRED

DELIVERED

b) UNRELIABLE SUPPRESSION

REQUIRED

DELIVERED

c) FAILED SUPPRESSION

FIGURE 6

CAUSES OF FAILED SUPPRESSION

MASS OF SUPPRESSANT

REQUIRED

DELIVERED

(a) TOO LATE

(b) TOO SLOW

(c) INSUFFICIENT

FIGURE 7
SF₆, SF₄, . . . F) attach electrons to form negative ions, the mobility of which is so small that they do not participate in current transport. Electrons diffusing out of the thin residual channel are attached, and thus the rapid rise in resistance is enhanced.

To describe the quenching processes theoretically, attempts were made in 1933 by Cassie and 1943 by Mayr using differential equations for the arc resistance based on the energy balance of the plasma column. Combinations of the two models by Browne Jr, and extensions by E Schmidt for instance, were able to give valuable insights into the current and voltage behaviour of breakers near current-zero.

Newer and more refined arc models use systems of partial differential equations of gas- and electrodynamics. Although very encouraging results have been achieved, all models must introduce a number of unknown constants which must be fitted to the experimental data. For the readers interested in a detailed treatment Swanson (1978) has given an extensive comparison of these models.

Some present and future problems
The general aim at all voltage levels is to increase the breaking capacity by increasing the current as well as the voltage per break. To realise the EHV and UHV transmission systems, voltages of 245 kV per break are envisaged. In such systems not only the interruption but also the closing causes difficulties because of high switching overvoltages. Another trend is to shorten the switching time to two cycles.

Finally, high-voltage DC transmission should be mentioned, for it has advantages if energy is to be transmitted over very large distances. Since up to now high-voltage DC interrupters do not exist, such systems can only be run between two sites.

There are thus still a large number of problems to be solved in the breaker field which are challenging both from the scientific and the technical points of view.

Further reading
Schmelcher T 1973 *Niederspannungsschaltgeräte. Siemens Fachbücher* (Berlin and Munich: Siemens Aktiengesellschaft)
Slamecka E 1966 *Prüfung von Hochspannungs- leistungsschaltern* (Berlin-Heidelberg-New York: Springer-Verlag)

Peter Edwin Moore is Principal Research Scientist at Graviner Ltd (Poyle Road, Colnbrook, Slough, SL3 0HA, England), a Wilkinson Match company. He has for several years led a team studying the physics of the explosion and suppression processes, and is now working on better explosion suppression systems for industrial plant. He is also a member of the UK delegation on the International Standards Organisation committee ISO/TC21/SC5/WG3.
It is common knowledge that flammable gases and vapours, when mixed with air, can form explosive mixtures; but it is less widely recognised that many everyday materials, such as flour, coffee and milk powder, can form explosible dust clouds. In December 1977, 54 lives were lost in a series of grain elevator dust explosions in the USA, and in the 15 years 1962-76, 21 fatalities and 601 injuries occurred in 432 separate incidents in the United Kingdom in which the ignition of dust was the primary cause. In addition, industrial plant and factory buildings suffered considerable and costly damage. In certain instances the shock wave from a localised explosion has disturbed accumulations of dust from the floor, sills, girders, etc, and thus created conditions for a secondary dust explosion which then propagated through the factory. The consequences of one such incident are shown in figure 1.

Manufacturing and processing industries are required to take all practical steps to prevent or restrict the propagation of explosions in industrial plant. In many processing and storage areas it is impractical to prevent the formation of dust or vapour clouds, and protection measures must be taken to minimise the effect of an explosion. The processing plant can be purged with nitrogen, thus preventing the formation of explosive mixtures. Alternatively, the build-up of destructive pressures in plant can be prevented by using either venting or explosion suppression procedures. These latter procedures are effective because explosions of vapour and dust clouds are not instantaneous occurrences. Typically the flame commences at a localised ignition source and grows spherically at velocities of 1–10 m s⁻¹. It follows that the larger the vessel, the longer is the time taken to reach a given pressure. Figure 2 shows that the time available for effective explosion countermeasures is only a few tens of milliseconds for the smaller volumes.

Before explosion protection measures can be designed it is necessary to ascertain the level of the explosion hazard. This article will identify the various factors that influence explosion severity, and outline some of the problems in hazard assessment. After briefly discussing venting, a detailed description of explosion suppression measures, using both liquid and powder suppressants, will be given, and the design criteria for explosion suppression systems discussed. An account of the detection of fires and explosions was provided in an article in an earlier issue of *Physics in Technology* (Ray 1978).

**Hazard assessment**

To assess the risk level of a particular material it is necessary to establish the most severe explosion that can be produced with it. Explosion severity is usually quantified in terms of the maximum explosion pressure, $P_{\text{max}}$, and the maximum rate of pressure rise, $(dP/dt)_{\text{max}}$, at the most explosible fuel concentration. The course of the explosion will be influenced by the nature and location of the ignition source, the level of turbulence, the homogeneity of the explosive mixture, vessel geometry, and environmental factors such as temperature and humidity.

The explosibility of a fuel is determined in a standard test apparatus. The measured explosion pressure, $P_{\text{max}}$, is essentially independent of vessel volume $V$, whereas the maximum rate of pressure rise, $(dP/dt)_{\text{max}}$, obeys a cube law relationship:

$$\frac{dP}{dt_{\text{max}}} \cdot V^{1/3} = K (\text{explosion rate constant}).$$

Since it is not possible to produce a quiescent dust/air suspension, account must be taken of the level of turbulence, $z$, in the experimental procedure:

$$\frac{dP}{dt_{\text{max}}} \cdot V^{1/3} = 2K_q$$

where $K_q$ is the explosion rate constant of the quies-
unsuppressed turbulent cellulose dust explosions

Figure 2 Pressure-time histories of suppressed and unsuppressed turbulent cellulose dust explosions

Hartmann data also can be in error because the measured explosibility is dependent on the ignition sensitivity of the dust. Thus a dust which is difficult to ignite will have a low Hartmann explosibility rating; but in a larger volume with a higher energy ignition source it could explode violently. An example of such a material is powered milk which has an explosibility rate constant of $4 \text{bar m s}^{-1} (-400 \text{ kPa m s}^{-1})$ measured in the Hartmann apparatus, and $92 \text{bar m s}^{-1}$ measured in a larger apparatus. The design of explosion protection measures based on the Hartmann determination could result in inadequate protection. It has been shown recently that $20 \text{dm}^3$ is the smallest volume of apparatus which gives results consistent with those obtained in large ($>1 \text{m}^3$) apparatus.

Venting

Explosion venting is a simple means of explosion protection. Weak vent panels are incorporated into the structure of industrial plant, and the pressure generated by the developing explosion ruptures these panels, thereby limiting the build-up of destructive pressures in the plant. With this means of protection the full force of the explosion is released into the environment. Venting countermeasures therefore require a large safe area surrounding each vent panel, since burning material can be thrust some ten or more metres and the considerable sonic blast will be heard over a very large area.

The recommended vent area is defined with reference to the fuel explosibility which is currently based on Hartmann apparatus measurements in the UK.

Explosion suppression

Explosion suppression requires that the explosion is detected very soon after its inception, and that sufficient suppressant is delivered into the growing fireball to quench or suppress it before destructive pressure is developed in the plant. Most industrial plants in the processing industry cannot withstand overpressures much greater than $0.3 \text{bar}$ ($30 \text{kPa}$). Typically explosion suppression countermeasures can restrict pressure build-up to below $0.2 \text{bar}$. The explosion is contained within the plant, and hence the environmental hazards prevalent with venting are avoided.

The action of suppressants

An explosion can be described as a freely propagating combustion wave in a flammable fuel–air mixture. The rate of propagation may be physically or chemically controlled. As a generalisation, combustion reaction kinetics are considered to control flame propagation in gas explosions, whereas heat transfer between particles is considered to control the propagation rate of dust explosions. Hence to suppress a gas explosion it is necessary to inhibit the combustion reactions, whereas to suppress most dust explosions one requirement is to quench the combustion wave. However, such a simple distinction cannot always be made in practice.

The consequence of discharging a spray of liquid or powder suppressant into a growing fireball is complex.
Numerous effects can be identified, any of which may be principally responsible for the suppression of a particular explosion. Some of these effects are:
(a) Free radical scavenging – active species in the suppressant inhibit the combustion chain propagating reactions.
(b) Advanced inerting – the concentration of suppressant injected into the unburned explosive mixture can render the mixture nonflammable.
(c) Thermal quenching – cooling of combustion zone and combustion products.
(d) Physical quenching – unburned particles or droplets are caused to agglomerate such that non-explosive conditions prevail.

Evaporation rate per unit of surface area, chemical specificity, thermal capacity and residence time in the combustion zone all have an influence on the effectiveness of liquid droplets and powder particles as suppressants. The discharge profiles of suppressors, particle–droplet size distributions, and suppressant concentration levels all influence suppression effectiveness.

**Explosion detection**

It is evident from figure 2 that to restrict the pressure build-up in a plant to, say 0.3 bar, it is necessary to detect the onset of an explosion before the pressure has exceeded 0.1 bar. In industrial practice, explosions are detected by means of either radiation or pressure detectors. For dust explosions, pressure detection is the usual choice because the radiation from the fireball may be obscured by the dust cloud. Figure 4a shows a pressure threshold detector which has general applicability, except in plant processing areas where normal pressure fluctuations may temporarily exceed the threshold level for which activation is necessary. For such applications, and for smaller volume installations, a rate-of-rise pressure detector is more suitable. This type of detector has an upper threshold pressure setting to ensure that ‘slow’ explosions are also detected.

The choice of detector, and of detector settings, depends on the nature of the hazard, the estimated explosion severity and the plant operating conditions. Typical settings of threshold and rate-of-rise detectors are 0.035 bar and 0.8 bar s$^{-1}$ respectively.

**Explosion suppressors**

There is a wide range of explosion suppression hardware available to the application engineer designing an explosion suppression system. The selection of the appropriate hardware for a particular application requires not only an assessment of the hazard, but also a knowledge of the performance capabilities of the hardware.

Figure 4b shows a sectioned hemispherical type of suppressor which can deliver liquid suppressant within 5 ms of detection, and with an initial discharge velocity in excess of 200 m s$^{-1}$. The hydraulic shock, which is generated by an electrically fired explosive charge in the centre of the suppressant, ‘petals’ the scored frangible dome and thrusts the suppressant into the plant. These suppressors are available in capacities of 0.5, 1.0 and 5.0 dm$^3$. Since they are fixed inside the plant they are unsuited to high-temperature industrial processes. The hemispherical suppressor is exceptionally fast, but has a limited discharge range, typically $<$ 2.5 m. It is particularly suited to ducting and small-volume container applications.

High-rate discharge (HRD) suppressors which can deliver liquid or powder suppressant are available with capacities in the range 4–70 kg. A 75 mm outlet system, a 20 mm outlet system and a double outlet 20 mm system are marketed. The suppressant is contained in a canister under a high pressure of nitrogen. Figure 4c shows one of the range of 75 mm outlet high-rate discharge suppressors designed for a

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*Figure 4 Explosion suppression hardware: a: Detector, b: Hemispherical suppressor, c: High-rate discharge suppressor*
liquid suppressant. A frangible disc across the outlet orifice is ruptured by the hydraulic shock generated by an electrically fired detonator, and the suppressant is ejected from the canister by the compressed nitrogen. A 'pepper pot' spreader disperses the liquid as a fine mist into the plant. This type of suppressor typically has a delay of some 10–15 ms between activation and suppressant appearing at the spreader. The suppressant discharge velocity is about 50 m s\(^{-1}\) and the mass discharge rate is about 100 kg s\(^{-1}\) for the first 25 ms; then it decreases. The choice of propelling agent pressure influences the performance of a HRD suppressor. The higher the pressure, the higher the discharge velocity, but the higher is the overpressure injected into the plant as a consequence of discharging the suppressor. Powder systems use higher propelling agent pressures than liquid systems in order to achieve effective dispersion of the powder.

HRD suppressors are used in larger installations where more time is available for suppression, because of the lower rate of pressure development, but a greater suppressant throw is required.

**The explosion suppression system**

Although general guidelines are available, explosion suppression installations have to be carefully designed for each application. Complete plant protection may include high-speed isolation valves and inerting countermeasures to restrict flame passage down interconnecting ducting. A central control unit provides continuous monitoring of external circuits, and will initiate plant shut-down in the event of an explosion.

Figure 5 shows typical explosion suppression countermeasures for a grinder/cyclone processing system. The grinder and ducting are protected by hemispherical suppressors. An explosion in the grinder will be detected by detector D1 and suppressed by the hemispherical suppressors in the grinder. The halon injected into the ducting will prevent flame propagation to the cyclone. Similarly an explosion in the cyclone will be detected by detector D2 and suppressed by the HRD suppressors. Flame propagation to the grinder is prevented by the hemispherical suppressors in the ducting, and a high-speed isolation valve will isolate this system from the rest of the plant in the event of an activation. A 20 mm HRD suppressor prevents any flame propagation beyond this valve as it closes. Since an explosion could start anywhere in this processing area, operation of either of the detectors will cause the whole suppression system to operate—thus ensuring complete plant protection.

Apart from the noise of the suppressors firing, the only indication of a suppressed explosion event to a plant operator is the automatic shut-down of the plant. The duration from ignition to suppression is typically less than 300 ms, and the only identifiable evidence of an explosion will be a small quantity of charred material in the processing plant, if dust was involved.

**System testing**

The effectiveness of explosion suppression countermeasures against both gas and dust explosions are determined in large test apparatus—typically of 1–60 m\(^3\) volume. Figure 6 shows a 5 m\(^3\) test facility which is capable of withstanding 30 bar overpressure. Therefore it can contain unsuppressed explosions and the limits of effectiveness of explosion suppression systems, against quantified explosion severities, can be fully explored. In particular, the effect of increasing the detection pressure, and the effect of reducing suppressant concentration, are studied in order to provide vital information for the engineer designing explosion suppression systems.

A series of collaborative trials were recently undertaken by UK/USA/German/Swiss and French members of a working group of the International Standards Organisation to assist in the formulation of an international code of practice for the application of explosion suppression systems to industrial plant. The effectiveness of three of the most commonly used explosion suppressants:

(a) Water

(b) Halon 1011 (chlorobromomethane CH\(_2\)BrCl)

(c) Tropolar (ammonium phosphate powder)

against both gas and dust explosions was evaluated. These tests were undertaken using a double outlet 20 mm HRD suppressor, or alternatively a single outlet 75 mm HRD suppressor in a 1 m\(^3\) chamber, and two 75 mm HRD suppressors in a 3.8 m\(^3\) vessel. The results are summarised in Table 1. The following observations can be made:

(a) Water is not an effective suppressant of gas explosions, but is effective against certain dust explosions.

(b) In general the 75 mm HRD system is more effective than the double-outlet 20 mm HRD system.

(c) More effective suppression was achieved in the larger test volume where more time was available to suppress the explosion.

(d) In general, Halon 1011 and Tropolar powder have similar levels of effectiveness. However, certain tests
demonstrated that Halon 1011 can fail to suppress the explosion if a high detection pressure is used.

System design
Whilst testing provides valuable information on the effectiveness of alternative explosion suppression measures against a range of hazardous materials, it is obviously impractical to validate each specific industrial system design. Interpretation of suppression test data obtained in one volume to an alternative volume and suppression system configuration is not straightforward. In a larger volume the pressure build-up is slower, thus there is more time available for suppression; but the explosion energy at detection is greater and the suppressant has to be thrown further. In a smaller volume the pressure build-up is much faster and any inertia in the explosion suppression system will be a major factor in the system performance.

Account must be taken of a large number of parameters when designing explosion suppression measures for industry (see table 2). The choice of detector and of suppressant depends on the type of industrial process. The strategy adopted in the UK and USA is to seek to contain the explosion without recourse to strengthening the plant structure. Liquid suppressant is the usual choice for this purpose, because of its superior discharge characteristics. Particular advantages of the Halon suppressants are that risk of product contamination (which is particularly important in the food and pharmaceutical industries) is minimised, and that its nonflammable vapour persists in the plant, preventing any possibility of re-ignition. Powder suppressants are particularly useful where a very violent explosion hazard prevails, or plant processing conditions demand very high detection pressures as a prerequisite. For such installations it is necessary to strengthen the industrial plant such that it is shock resistant to a pressure pulse of 1 bar. This latter strategy is widely adopted in Germany.

Explosion suppression measures are designed and optimised for each specific application with the aid of mathematical models and computer simulation techniques. Such mathematical tools must take account of the numerous factors that influence industrial hazards and suppression system performance which are listed in table 2. Computer modelling enables the simulation of the pressure/time and fireball radius–time histories of the severest explosions possible in a particular plant and hence allows the suppression effectiveness of a proposed system to be predicted.

Conclusions
Although much progress has been made, the complexities of industrial processes are such that much more research is needed before we will understand the physics of explosions, and of their suppression, sufficiently to be able to cope with all types of explosion. To this end, the international cooperation, which is being actively encouraged by governments and industries in several countries, is aimed at defining precise standards for hazard assessment and suppression system effectiveness.

As industries become more aware of the nature and the causes of explosion hazards new plants are having more effective countermeasures incorporated at the design stage, and are having their processes modified to minimise the hazards. The result is that the industrial environment is becoming increasingly safer.

Further reading
Bartknecht W 1978 Explosionen Ablauf und Schutzmaßnahmen (Berlin: Springer Verlag)

Figure 6 Graviner 5 m³ explosion test apparatus
and a number of regional agencies for scientific and technical information (ARIST) which undertake technical studies on the state of development of products, survey technical literature, assist in developing new strategies, etc, in response to requests from firms.

In 1975 the MI set up a scheme of growth contracts (contrats de croissance) whereby viable firms in sectors considered to be of particular economic significance receive aid in return for an undertaking to achieve targets concerning production, employment, exports and the domestic market share. By 1977 contracts had been set up in four sectors: computer peripherals, scientific/medical instruments, electronic components and machine tools.

† French Government Assistance for Industrial Research and Development by J E Macrae and Dr M W Jones, Department of Industry 'Science and technology abroad' FRA 149.

Apologies

In the September issue of Physics in Technology the article by Peter Moore on 'Explosion suppression in industry' (1979 10 202-7) was unfortunately printed with two tables missing. These are now reproduced with apologies for any inconvenience caused. Apologies are also made for the reversed figure 2 on p197 in the article by W Hertz, and for the spurious reference to figure 6 (p221) in the article by L H Th Rietjens.

Table 1 Results of evaluation tests on three common suppressants for gas and dust explosions. A, < 0.3; B, 0.3–1; C, 1–3; D, 3–P_max; F, ≥ P_max (values in bar)

<table>
<thead>
<tr>
<th>Explosible fuel</th>
<th>Explosion suppressant</th>
<th>Detection pressure (bar)</th>
<th>Suppressed explosion pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>20 mm HRD system</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>V = 1 m³</td>
</tr>
<tr>
<td>Water</td>
<td>0.1</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>'Propane' gas</td>
<td>0.3</td>
<td>F</td>
<td>A</td>
</tr>
<tr>
<td>Tropolar</td>
<td>0.3</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Water</td>
<td>0.3</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Cellulose dust</td>
<td>0.1</td>
<td>D</td>
<td>B</td>
</tr>
<tr>
<td>Tropolar</td>
<td>0.3</td>
<td>F</td>
<td>C</td>
</tr>
</tbody>
</table>

Table 2 Parameters for consideration when designing explosion suppression measures for industry

<table>
<thead>
<tr>
<th>Nature of hazard</th>
<th>The industrial process</th>
<th>The suppressors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured explosibility parameters:</td>
<td>Volume and geometry of plant</td>
<td>Numbers, type and geometric configuration</td>
</tr>
<tr>
<td>Most exploisible concentration</td>
<td>Maximum turbulence level</td>
<td>Response time</td>
</tr>
<tr>
<td>Maximum explosion pressure</td>
<td>Product throughput</td>
<td>Discharge velocity and mass discharge rate</td>
</tr>
<tr>
<td>Maximum rate of pressure rise</td>
<td>Plant operating pressures:</td>
<td>Spatial and temporal discharge profiles</td>
</tr>
<tr>
<td>Normal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant strength</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Type of explosion: | | |
| Gaseous | | |
| Dust cloud | | |
| Liquid spray cloud | | |
| Hybrid | | |

| The system | | |
| Advanced inerting requirements | | |
| Isolation requirements | | |

| The detectors | | |
| Numbers, type and geometric location | | |
| Sensitivity | | |
| Response time | | |

| The suppressant | | |
| Droplet/particle size and shape distribution | | |
| Evaporation rate | | |
| Thermal capacity | | |
| Chemical specificity | | |
La soppressione delle esplosioni nelle industrie.

P. E. Moore

Con i sensori opportuni ed une attrezzatura ben progettata, esplosioni in teoria catastrofiche possono diventare semplici cause d'interruzione del l'impianto, con danno molto minore.

È comunemente noto che gas e vapori infiammabili possono formare miscugi esplosivi, se misti con aria; ma non si è ugualmente acquisito che molti materiali comuni, come farina, caffè e latte in polvere, possono formare nubi di polvere esplosiva. Nel dicembre 1977, 54 persone morirono in una serie di esplosioni di polvere in un trasportatore di grano negli USA, e nei 15 anni tra il 1962 e il 1976 ci furono 21 morti e 601 feriti in 432 diversi incidenti nel Regno Unito, tutti causati originariamente da accensione di polvere. Inoltre le attrezzature e gli stabili delle industrie accusarono gravi e costosi danni. In alcuni casi l'onda d'urto propagatasi da un'esplosione localizzata ha perturbato l'accumularsi di polvere dal pavimento, da longheroni, da travi, ecc., creando così le condizioni per un'ulteriore esplosione di polvere, che si è poi propagata attraverso l'edificio. Le conseguenze di un incidente di questo tipo sono mostrate in fig. 1.

Le industrie manifatturiere e di lavorazione sono tenute a compiere tutti i passi necessari per prevenire o ridurre la propagazione di esplosioni nelle attrezzature industriali. In molte aree di lavorazione ed immagazzinamento è impossibile impedire la formazione di nubi di polvere o vapore, e si devono quindi prendere misure di protezione per minimizzare l'effetto di un'esplosione. L'attrezzatura di lavoro deve essere depurata con azoto per impedire così la formazione di miscugi esplosivi.

Altrimenti il raggiungimento di una pressione distruttiva nell'impianto si può evitare o aprendo sfoghi o con procedure di soppressione dell'esplosione. Questi ultimi metodi sono efficaci, poiché le esplosioni di nubi di vapore e polvere non sono incidenti istantanei. Di solito la fiamma inizia in una localizzata sorgente di accensione e si allarga sfericamente a velocità di...
Fig. 1. - Conseguenze di un'esplosione secondaria di polveri: 5 morti (la fotografia è stata ottenuta per gentile concessione del HMSO, Londra).

\[(1 \pm 10) \text{ m/s. Pertanto, piú grande è il recipiente, maggiore è il tempo necessario a raggiungere una certa pressione.}\]

La fig. 2 mostra che il tempo disponibile a efficaci contromisure per l'esplosione è solo di qualche decina di millisecondi per i più piccoli volumi.

Prima di poter progettare misure di protezione per le esplosioni, è necessario verificare il grado di rischio di esplosione. In questo articolo si esamineranno i vari fattori che influenzano la gravità di un'esplosione e si esporranno alcuni dei problemi nella valutazione del rischio. Dopo un breve cenno sul metodo di apertura di sfoghi, si farà una dettagliata descrizione delle misure per bloccare l'esplosione, usando sia polveri che liquidi, e si discuteranno i criteri di progettazione di sistemi per soppressione di esplosioni. Un resoconto sulla rivelazione d'incendi ed esplosioni era stato dato in un articolo di un numero precedente di Physics in Technology (Ray 1978).
1. Valutazione del rischio.

Per valutare il grado di rischio di un certo materiale è necessario stabilire qual'è la più violenta esplosione che con esso si può produrre. Di solito si quantizza la violenza di un'esplosione in termini della massima pressione di esplosione, $P_{\text{max}}$, e della massima variazione di pressione, $(dP/dt)_{\text{max}}$, alla concentrazione di combustibile maggiormente esplosiva. Lo svolgersi dell'esplosione sarà influenzato dalla natura e dalla collocazione della sorgente d'accessione, dal livello di turbolenza, dall'omogeneità della miscela esplosiva, dalla geometria del contenitore, da fattori ambientali quali temperatura ed umidità.

La possibilità di esplodere di un carburante viene determinata in un impianto standard di test. La pressione di esplosione misurata, $P_{\text{max}}$, risulta indipendente dal volume $V$ del contenitore, mentre la variazione massima di pressione, $(dP/dt)_{\text{max}}$, obbedisce ad una legge cubica:

$$(dP/dt)_{\text{max}} V^{1/3} = K$$

(costante della velocità di esplosione).

Poiché non è possibile produrre una sospensione in equilibrio di polvere ed aria, si deve tener conto, in una procedura sperimentale, del livello di turbolenza $\alpha$:

$$(dP/dt)_{\text{max}} V^{1/3} = \alpha K_\alpha,$$

dove $K_\alpha$ è la costante di velocità di esplosione del combustibile in equilibrio. Si è dimostrato sperimentalmente che la turbolenza può fare aumentare $(dP/dt)_{\text{max}}$ di un fattore 10. I parametri che definiscono la possibilità di esplosione in condizioni di equilibrio di molti solventi in fase di vapore e gas infiammabili sono riportati nella letteratura. Sono riportati anche dati riguardanti molte polveri. Comunque, in pratica, si dovrebbe esaminare ogni specifica polvere industriale, dato che le dimensioni delle particelle, la loro varietà di forma, il contenuto di umidità e le impurità sono tutti fattori che possono avere marcata influenza sull'esplosività della polvere.

Fig. 3. – Apparecchiatura di prova di Hartmann.

La procedura comune nel Regno Unito è quella che esamina le polveri con un apparato standard di 1.23 dm$^3$ a tubo verticale del tipo di Hartmann mostrato in fig. 3. Studiosi tedeschi e svizzeri hanno dimostrato che il dispositivo di Hartmann sottostima l'esplosività delle polveri almeno di un fattore 2.5 e questo è in parte conseguenza del contenimento dell'esplosione alle pareti del tubo. Essi hanno suggerito di ottenere valutazioni dell'esplosività in apparati di grande volume (molto maggiori di 1 m$^3$). L'autore ha dimostrato che i dati di Hartmann possono anche risultare errati, poiché l'esplosività misurata risulta dipendere dall'infiammabi-
lità della polvere. Così una polvere poco infiammabile avrà un piccolo grado di esplosività, secondo Hartmann, ma in un volume più ampio con una sorgente di accensione a maggiore energia la stessa polvere potrebbe esplodere violentemente. Un esempio di un tale materiale è il latte in polvere, che ha una costante del grado di esplosività di 4 bar·m/s ($= 400$ kPa·m/s) misurato in un apparato di Hartmann e di 92 bar·m/s se misurato in un apparato più ampio. Il progetto di misure di protezione da esplosioni basato sulla determinazione di Hartmann potrebbe portare a protezioni inadeguate. Recentemente si è dimostrato che 20 dm$^3$ è il minimo volume di un apparato che dia risultati consistenti con quelli ottenuti in appareti più grandi ($>1$ m$^3$).

3. Soppresione dell’esplosione.
Il poter sopprimere un’esplosione richiede che questa sia individuata immediatamente dopo il suo innesco e che si liberi neutralizzatore a sufficienza nel centro dell’esplosione per spegnerla o impedirla prima che la pressione distruttiva si sviluppi nell’impianto. Molti impianti industriali non possono resistere a sovrappressioni molto maggiori di 0.3 bar ($= 30$ kPa). Contromisure tipiche per la soppressione di esplosioni possono contenere il formarsi di pressioni al di sotto di 0.2 bar. L’esplosione viene contenuta all’interno dell’impianto e quindi si evitano i rischi ambientali prevalenti nel metodo di sfogo.

4. L’azione dei soppressori.
Si può descrivere un’esplosione come un’onda di combustione che si propaga liberamente in una miscela infiammabile di aria e combustibile. La velocità di propagazione si può controllare fisicamente o chimicamente. Per generalizzare, si deve considerare la cinetica della reazione di combustione per controllare la velocità di propagazione della fiamma nell’esplosione di gas, mentre per controllare la stessa nell’esplosione di polveri occorre considerare il trasferimento di calore fra particelle. Pertanto, per sopprimere un’esplosione di gas, si devono neutralizzare le reazioni di combustione, mentre per sopprimere la maggior parte delle esplosioni di polveri occorre estinguere l’onda di combustione. Tuttavia una così semplice distinzione non sempre può valere nella pratica.
L’effetto dovuto allo spruzzare liquido o polvere di soppressione nel centro dell’esplosione è complesso. Si
La soppressione delle esplosioni nelle industrie

possono identificare vari processi, ognuno dei quali può risultare il principale responsabile della soppressione di un particolare tipo di esplosione. Alcuni di questi effetti sono:

a) Completa eliminazione – le specie attive del soppressore neutralizzano le reazioni che propagano la catena di combustione.

b) Neutralizzazione avanzata – la concentrazione di soppressore immesso nella miscela esplosiva incombusta può renderla non infiammabile.

c) Estinzione termica – raffreddamento della zona e dei prodotti di combustione.

d) Estinzione fisica – si provocano le agglomerazioni di particelle o gocce non bruciate in modo che prevalgano le condizioni di non esplosione.

La velocità di evaporazione per unità di superficie, la specificità chimica, la capacità termica ed il tempo di permanenza nella zona di combustione influenzano l'efficacia delle gocce di liquidi e delle particelle di polveri come soppressori. I profili di scarica di soppressori, le distribuzioni delle dimensioni delle particelle o delle gocce e i livelli di concentrazione del soppressore sono tutti fattori che influiscono sull'efficacia del metodo.

5. Rivelazione dell'esplosione.

È evidente dalla fig. 2 che, per contenere la pressione che si può formare in un impianto fino, ad esempio, a 0.3 bar, occorre rivelare l'inizio di un'esplosione prima che la pressione abbia superato 0.1 bar. Nella pratica industriale le esplosioni s'individuano per mezzo di misuratori di pressione o rivelatori di radiazione. Per le esplosioni di polveri si sceglie di solito il rivelazione della pressione, poiché la radiazione.
zione proveniente dal nucleo dell’esplosione può essere oscurata dalla nube di polvere. La fig. 4a) mostra un rivelatore di pressione a soglia largamente utilizzato, tranne che in ambienti in cui le normali fluttuazioni di pressione possono temporaneamente superare il livello di soglia corrispondente all’attivazione. Per tali applicazioni e per installazioni in volumi minori è più opportuno un misuratore della velocità di aumento della pressione. Questo strumento ha anche una soglia superiore di pressione che si può fissare per essere sicuri di rivelare anche le esplosioni più lente.

La scelta del rivelatore e delle sue condizioni d’intervento dipende dalla natura del rischio, dalla stima della violenza dell’esplosione, dalle condizioni di uso dell’impianto. Valori tipici dei punti di lavoro dei rivelatori a soglia e a velocità di aumento sono rispettivamente 0.035 bar e 0.8 bar·s⁻¹.


Esistono molti tipi di apparecchiature a disposizione di chi deve progettare un sistema per la soppressione di esplosioni. La scelta dell’attrezzatura adeguata per una particolare applicazione richiede non solo una valutazione del rischio, ma anche la conoscenza delle prestazioni dell’apparecchiatura.

La fig. 4b) mostra un soppressore ad emissario che può liberare liquido di spegnimento entro 5 ms dalla rivelazione e con una velocità di scarica iniziale superiore a 200 m/s. L’urto idraulico generato da una carica esplosiva accesa elettricamente nel centro del soppressore distrugge la cupola preincisa e forza il liquido nell’ambiente. Questi soppressori sono disponibili nelle dimensioni volumetriche di 0.5, 1 e 5 dm³. Dovendo essere fissati nell’impianto, non sono adatti per i processi industriali ad alte temperature. Il soppressore ad emissario è estremamente veloce, ma ha una portata limitata, di solito minore di 2.5 m. Risulta particolarmente adatto per applicazioni in condotti e contenitori di piccolo volume.

I soppressori ad alta velocità di scarica (HRD) che possono liberare liquidi o polveri sono disponibili con capacità variabili tra 4 e 70 kg. Esistono sul mercato sistemi ad apertura singola di 75 mm, 20 mm e a doppia apertura di 20 mm. Il soppressore è contenuto in un recipiente ad alta pressione singola di azoto ((20÷120) bar). La fig. 4c) mostra uno dei soppressori HRD con apertura da 75 mm per liquidi. L’urto idraulico generato da un detonatore innescato elettricamente rompe un disco posto nell’orifizio di uscita ed il liquido viene evacuato dal contenitore dall’azoto compresso. Un diffusore disperde il liquido a nebbia nell’impianto. Questo tipo di soppressore presenta di solito ritardi di (10÷15) ms fra il momento dell’attivazione e la fuoriuscita del liquido dal distributore. La velocità di uscita del liquido è circa 50 m/s e la portata in massa è circa 100 kg/s per i primi 25 ms, poi tende a diminuire. La scelta della pressione della sostanza che agisce da propulsore influenza la prestazione di un soppressore HRD. Tanto maggiore è la pressione, tanto più alta è la velocità di scarica, ma risulta anche maggiore l’incremento di pressione provocato nell’impianto come conseguenza della scarica del liquido. Sistemi a polvere utilizzano pressioni delle sostanze agenti da propulsore maggiori che i sistemi a liquido, e questo per ottenere un’efficace dispersione della pol-
7. Il sistema di soppressione di esplosioni.

Sebbene siano disponibili procedure generali, le installazioni per la soppressione di esplosioni devono essere accuratamente progettate per ogni applicazione. L'intera protezione dell'impianto può includere alcune valvole d'isolamento ad alta velocità ed adatte contromisure atte a limitare il passaggio del fuoco nei condotti di connessione. Un'unità centrale controlla con continuità i circuiti esterni e può far cominciare la chiusura dell'impianto in caso di esplosione.

![Diagrama](https://via.placeholder.com/150)

La fig. 5 mostra un'apparecchiatura tipica per la soppressione di esplosioni in un sistema di lavorazione macina-ciclone. La macina e il condotto sono protetti da soppressori ad emisfero. Un'esplosione nella macina sarà rivellata dal rivelatore D1 e neutralizzata dai soppressori emisferici nella macina. Halon iniettato nel condotto impedirà all'incendio di propagarsi nel ciclone. Analogamente un'esplosione nel ciclone sarà rivellata dal rivelatore D2 e blocata dai soppressori HRD. La propagazione di fiamma nella macina viene impedita dai soppressori emisferici nel condotto e la valvola d'isolamento ad alta velocità isola questo sistema dal resto dell'attrezzatura in caso di attivazione. Un soppressore HRD da 20 mm impedisce la propagazione della fiamma oltre la valvola quando essa è chiusa. Poiché un'esplosione potrebbe iniziare ovunque in questa area di lavorazione, l'azione di ciascuno dei rivelatori provoca il blocco del sistema, assicurando così una totale protezione dell'impianto.

Eccettuato il rumore dell'accensione del soppressore, la sola indicazione dell'avvenuta soppressione di esplosione è la chiusura automatica dell'impianto. Il tempo che trascorre dall'innesto alla soppressione è in genere minore di 300 ms e l'unica prova identificabile di un'esplosione sarà una piccola quantità di materiale carbonizzato nell'impianto di lavorazione, se era presente della polvere.

8. Prova del sistema.

L'efficacia di contromisure per la soppressione di esplosioni sia di gas che di polveri viene determinata in apparati di prova di grandi dimensioni, tipicamente di $(1 \pm 60)$ m³ di volume. La fig. 6 mostra un'attrezzatura di prova di 5 m³ in grado di sopportare sovrappressioni di 30 bar, perciò può
contenere esplosioni non soppresse e si possono esaminare dettagliatamente i limiti di efficacia delle misure di soppressione di esplosioni rispetto alla grandezza della gravità dell’esplosione.

Fig. 6. - Apparecchiatura Graviner da 5 m³ di prova di esplosione.

In particolare si studiano l’effetto di un aumento del valore della pressione rivelata e l’effetto di riduzione della concentrazione di soppressore allo scopo di fornire informazioni vitali al progettista di sistemi di soppressione.

È stata recentemente intrapresa una serie di esperimenti in collaborazione (Gran Bretagna, USA, Germania, Svizzera e Francia) nell’ambito di un gruppo di lavoro della International Standards Organisation per giungere alla formulazione di un codice di uso internazionale per l’applicazione di sistemi di soppressione di esplosioni per impianti industriali. È stata valutata l’efficacia di tre neutralizzatori di esplosione sia di gas che di polveri fra i più comunemente usati:

a) acqua,
b) Halon 1011 (clorobromometano CH₂BrCl),
c) Tropolar (fosfato di ammonio in polvere).

Queste prove sono state condotte usando un soppressore HRD a doppia uscita da 20 mm o, in alternativa, uno a

<p>| Tabella I. |</p>
<table>
<thead>
<tr>
<th>Combustibile esplosivo</th>
<th>Soppressore di esplosione</th>
<th>Pressione di rivelazione (bar)</th>
<th>Efficacia della soppressione</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$V = 1 \text{ m}^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>sistema HRD da 20 mm</td>
</tr>
<tr>
<td>Gas propano</td>
<td>Acqua</td>
<td>0.1</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>Halon 1011</td>
<td>0.1</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>Tropolar</td>
<td>0.1</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>F</td>
</tr>
<tr>
<td>Polvere di cellulosa</td>
<td>Acqua</td>
<td>0.1</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Halon 1011</td>
<td>0.1</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Tropolar</td>
<td>0.1</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>D</td>
</tr>
</tbody>
</table>

$A$ - pressione dell'esplosione soppressa $< 0.3$ bar;
$B$ - pressione dell'esplosione soppressa $(0.3 - 1.0)$ bar;
$C$ - pressione dell'esplosione soppressa $(1.0 - 3.0)$ bar;
$D$ - pressione dell'esplosione soppressa $(3.0 - P_{\text{max}})$ bar;
$F$ - pressione dell'esplosione soppressa $> P_{\text{max}}$. 

P. E. Moore
La soppressione delle esplosioni nelle industrie

La soppressione delle esplosioni nelle industrie

singola uscita di 75 mm in una camera di 1 m³ e due soppressori HRD da 75 mm in un contenitore di 3.8 m³. I risultati sono indicati nella tabella I.

Si possono fare le seguenti osservazioni:

a) l’acqua non è un efficace neutralizzatore di esplosioni di gas, ma risulta tale per alcune esplosioni di polveri;

b) in generale il sistema HRD da 75 mm è più efficace di quello a doppia uscita da 20 mm;

c) si è conseguita una soppressione più efficace nel volume di prova più ampio in cui era disponibile un tempo maggiore per bloccare l’esplosione;

d) in generale l’Halon 1011 e la polvere Tropolar hanno livelli simili di efficacia. Comunque alcune prove hanno dimostrato che l’Halon 1011 può risultare inefficace se si usa un’alta pressione di rivelazione.


Mentre le prove forniscono valide informazioni sull’efficacia di svariate misure per la soppressione di esplosioni per un certo numero di materiali pericolosi, non è chiaramente pratico verificare ogni specifico progetto di sistema per l’industria. L’estrapolazione dei dati delle prove ottenuti in un volume ad un’altro volume o ad un’altra configurazione del sistema di soppressione non è sempre semplice. In un volume più ampio l’aumento di pressione è più lento e c’è quindi più tempo disponibile per la soppressione, ma l’energia di esplosione all’atto della rivelazione è maggiore e il neutralizzatore deve essere iniettato a maggiore distanza. In un volume minore la pressione aumenta più velocemente e l’inierenza del sistema di soppressione di esplosione sarà il fattore più importante nel determinare le prestazioni del sistema.

Nel progettare misure di soppressione di esplosioni per l’industria si deve tener conto di molti parametri (vedi tabella II).

<table>
<thead>
<tr>
<th>Tabella II.</th>
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</thead>
<tbody>
<tr>
<td><strong>Natura del rischio</strong></td>
</tr>
<tr>
<td>Parametri dell’esplosività misurati:</td>
</tr>
<tr>
<td>a) concentrazione maggiormente esplosiva,</td>
</tr>
<tr>
<td>b) valor massimo della $P$ di esplosione,</td>
</tr>
<tr>
<td>c) massima velocità di aumento di $P$.</td>
</tr>
<tr>
<td>Tipo di esplosione:</td>
</tr>
<tr>
<td>a) gassosa,</td>
</tr>
<tr>
<td>b) a nube di polvere,</td>
</tr>
<tr>
<td>c) a nube di vapore di liquidi,</td>
</tr>
<tr>
<td>d) ibrida.</td>
</tr>
<tr>
<td><strong>Il processo industriale</strong></td>
</tr>
<tr>
<td>Volume e geometria dell’impianto.</td>
</tr>
<tr>
<td>Massimo livello di turbolenza.</td>
</tr>
<tr>
<td>Presenza di prodotto.</td>
</tr>
<tr>
<td>Pressioni esistenti nell’impianto:</td>
</tr>
<tr>
<td>a) normale,</td>
</tr>
<tr>
<td>b) massima.</td>
</tr>
<tr>
<td>Resistenza dell’impianto.</td>
</tr>
<tr>
<td><strong>I neutralizzatori</strong></td>
</tr>
<tr>
<td>Tipo.</td>
</tr>
<tr>
<td>Distribuzione delle dimensioni e delle forme delle gocce/particelle.</td>
</tr>
<tr>
<td>Gesto di evaporazione.</td>
</tr>
<tr>
<td>Capacità termica.</td>
</tr>
<tr>
<td>Specificità chimica.</td>
</tr>
<tr>
<td><strong>I soppressori</strong></td>
</tr>
<tr>
<td>Numero, tipo e configurazione geometrica.</td>
</tr>
<tr>
<td>Tempo di risposta.</td>
</tr>
<tr>
<td>Velocità di scarica e quantità di massa scaricata.</td>
</tr>
<tr>
<td>Profili spaziali e temporali della scarica.</td>
</tr>
<tr>
<td><strong>I rivelatori</strong></td>
</tr>
<tr>
<td>Numero, tipo e collocazione geometrica.</td>
</tr>
<tr>
<td>Sensibilità.</td>
</tr>
<tr>
<td>Tempo di risposta.</td>
</tr>
<tr>
<td><strong>Il sistema</strong></td>
</tr>
<tr>
<td>Esigenze di neutralizzazione avanzata.</td>
</tr>
<tr>
<td>Esigenze d’isolamento.</td>
</tr>
</tbody>
</table>

La scelta del rivelatore e del soppressore dipende dal tipo di processo industriale, Il metodo adottato in Gran Bretagna e negli USA è cercare di contenere l’esplosione senza rinforzare la struttura del-
l'impianto. Il soppressore liquido è quello di solito usato per questo scopo; date le sue migliorie caratteristiche d'iniezione nell'impianto. Il soppressore Halon ha il particolare vantaggio di minimizzare il rischio di contaminazione del prodotto (cosa particolarmente importante nelle industrie alimentari e farmaceutiche); inoltre il persistere del suo vapore non infiammabile nell'impianto previene ogni possibilità di reinnescimento. I soppressori a polveri sono particolarmente utili quando sussiste il rischio di un'esplosione molto violenta o le condizioni di lavorazione nell'impianto richiedono pressioni di rivelazione molto alte. Per tali installazioni è necessario rinforzare le strutture dell'impianto in modo che esse possano sopportare impulsi di pressione fino ad 1 bar. Quest'ultimo metodo è largamente usato in Germania.

Le misure di soppressione di esplosione sono progettate ed ottimizzate per ogni specifica applicazione con l'aiuto di modelli matematici e di tecniche di simulazione al calcolatore. Questi strumenti matematici devono tenere conto dei vari fattori che influenzano i rischi industriali e le prestazioni del sistema di soppressione che sono indicati in tabella II. Il modello al calcolatore permette la simulazione di andamenti temporali della pressione e del raggio della sfera di esplosione delle più gravi esplosioni possibili in un particolare impianto e dunque consente di predire l'efficacia del sistema proposto.

10. Conclusioni.
Nonostante siano stati fatti molti progressi, la complessità dei processi industriali è tale che occorrono ancora molte ricerche prima di comprendere la fisica delle esplosioni e della loro soppressione fino ad essere in grado di affrontare ogni tipo di esplosione. A questo scopo, la cooperazione internazionale, che è stata largamente incoraggiata dai governi e dalle industrie di svariate nazioni, deve definire precisi standard di valutazione del rischio e dell'efficacia del sistema di soppressione. Poiché le industrie divengono più consapevoli della natura e dei rischi di un'esplosione, le nuove attrezzature hanno incorporate contromisure più efficaci in stadio di progetto ed i processi sono stati modificati per minimizzare i rischi. Il risultato è che l'ambiente industriale diventa via via sempre più sicuro.

ULTERIORI LETTURE

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