Fire safety testing of conveyor belts

Prepared by
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for the Health and Safety Executive
Fire safety testing of conveyor belts

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This research project, which was carried out under the Health and Safety Executive’s (HSE’s) Research Strategy Unit (RSU) contract reference 4167/R04.085, had three objectives. They were:

● to characterise the test gallery used in the UK for conveyor belt approvals;
● to identify and develop small scale laboratory tests that could be used to examine the behaviour of conveyor belts in the absence of the large scale facility; and
● to obtain some understanding of the importance of changes in test conditions on the performance of belts currently approved for use in coal mines.

The project satisfactorily achieved these objectives. A new test method has been provided together with drawings of the apparatus needed and proposed acceptance levels.

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EXECUTIVE SUMMARY

1 INTRODUCTION

Conveyor belts are widely used for transporting minerals in mines as well as in many other industrial situations. Because they contain large amounts of polymeric materials their use in certain environments, especially coal mines, but also in steel works, power stations and other enclosed areas must be controlled to minimise the fire risk.

Tests have been developed which belts must pass to be accepted for use in safety-critical situations. For underground mines the fire-resistance tests are the same for textile carcase and steel cord belts. They are contained in BS 3289:1990 and the technically identical British Coal Specification 158:1989 for textile carcase belts and in British Coal Specification 730:1989 for steel cord belts. In a mine tunnel, if the belt is ignited, the fire could spread along the belt (propagate) if it does not self-extinguish. This report is concerned with tests designed to examine the resistance of conveyor belts to the propagation of fire along their length.

Four different types of conveyor belt fire propagation tests are currently specified in the European Union for the acceptance testing of belts for use in coal mines. The tests vary in the length of belt sample, type, intensity and duration of heat source and test gallery geometry. A comparison exercise carried out under the auspices of the ECSC in the early 1990’s and followed up later in the UK revealed that belts which met the acceptance requirements in some of the tests failed others, and some belts which performed well in certain tests burned out completely in others.

The fire propagation test gallery used in the UK closed at the end of September 2000. The loss of this facility means that the propagation test in BS 3289:1990 and British Coal Specifications 158:1989 and 730:1989 can no longer be carried out in the UK.

2 OBJECTIVES AND METHODOLOGY OF THE RESEARCH

2.1 OBJECTIVES

The work proposed for this project had three objectives:

- to provide a full characterisation of the test gallery used in the UK for conveyor belt approvals
- to identify, characterise and develop small scale laboratory tests that could be used to examine the behaviour of conveyor belts in the absence of the large scale facility, seeking to correlate performance in these tests with performance in the large gallery
- in view of the differing performances of belts in the various EC propagation tests, to seek to obtain some understanding of the importance of changes in test conditions on the performance of belts currently approved for use in coal mines by testing over a wider range of test conditions

A subsidiary objective of the work was to provide a method of giving guidance to the mining industry on the means to assess compliance with established industry requirements for fire resistance in the absence of the long-established propagation test or a laboratory test that would correlate with it.
2.2 METHODOLOGY

A series of tests was proposed in which detailed measurements would be used to characterise the gallery by providing a wider understanding of the temperature profile in and around the test piece in the gallery. These tests involved measurements of air temperatures and flows, oxygen depletion measurements and temperature profiles on the belts. The programme included tests with known heat inputs and tests on a limited range of belts of known performance. This approach was designed to provide not only an adequate characterisation of the gallery but also information for the development of smaller scale tests.

A survey of the information available from previous laboratory scale gallery tests was to be supplemented by further testing in laboratory scale galleries, making similar measurements to those for the full scale gallery and varying the test parameters to simulate the conditions in the large scale gallery obtained from the results of the gallery characterisation. This work was intended to provide the basis for the development of testing in a mid scale model gallery that could eventually be used to determine the performance of belts instead of the full scale gallery.

3 PROPAGATION TESTS CURRENTLY SPECIFIED

This section of the report provides a background to current testing practices and requirements in Europe and information on the development of the UK propagation test. It describes:

- EU fire propagation tests on conveyor belts,
- the UK fire test facility,
- the development of the test used in the UK to examine fire propagation on conveyor belts for underground use, and
- the work done within the EU on harmonisation of fire propagation tests

4 LITERATURE SURVEY

The report includes a detailed survey of the relevant literature. It includes:

- basic considerations of fire testing
- flame spread theory and its application to fire performance
- work done in Australia that had similar aims to the present study
- previous work with laboratory-scale tests.

The work included was selected on the basis of its direct relevance to the objectives set out in Section 2. It showed that a considerably amount of work has taken place on the subject of fire testing of conveyor belting and that good progress has been made in understanding the phenomena taking place in flame propagation.

5 EXPERIMENTAL WORK

The experimental work is in two parts. The first part was carried out using the former British Coal large scale fire gallery and the second using the mid-scale MSHA gallery at the premises of J H Fenner and Co Ltd.

Two types of tests were carried out in each gallery:

- Tests to characterise the gallery itself
Tests to characterise the performances of conveyor belts that were expected to give small, intermediate and large amounts of propagation.

The tests in the large-scale gallery were all made prior to any work being done in the MSHA gallery. The results from the large-scale gallery were used as the basis on which to develop the mid-scale gallery test. The test conditions in the MSHA gallery were varied as the work progressed in order to try to simulate the performance of the belts in the large-scale gallery.

Severe time constraints were imposed on the large-scale tests. The closure of the gallery, scheduled for the end of September 2000, left no opportunity for repeating any of the work in the event of problems. Equally, because of the closure there was no possibility of returning to the gallery after the work in the mid-scale gallery to confirm correlations in performance.

### 5.1 LARGE-SCALE GALLERY RESULTS

From the results of the characterisation tests it was possible to derive relationships that were useful for understanding how the large gallery might relate to the mid-scale equipment and that would be helpful if the need arose for a large scale gallery to be constructed to reproduce the characteristics of this facility in the future. These were:

- Relationships between the air velocity measurements made by the portable anemometer, the array of anemometers and the differential pressure transducer in the duct
- Values for the power of the calibration fires (heat release rates) calculated from the quantity of gas consumed, the oxygen consumption measurements and the temperature rise values.
- Equations describing the temperature rise curves
- Measures of the performance of three conveyor belts of different types, including extent of damage, temperature profiles along the belt samples and flame front velocities.

The possible effect of a reduced heat input was examined to determine whether the validity of the test results is affected i.e. whether the test is a true test of resistance to propagation and whether the length of belt damaged is affected. The critical factor appeared to be that sufficient heat is put into the belt over the burner for it to become fully alight and burn away. The burning belt thus becomes the principal source of heat input to the unburned belt in the critical area for resistance to propagation to be measured i.e. the region just beyond the influence of the burner. Since the belt was burned away over the burner in all of the tests made in this work it could be argued that the amount of gas used is more than sufficient and that the test is a true test of resistance to propagation.

### 5.2 MID-SCALE GALLERY TESTS

The MSHA mid-scale gallery was identified as a potentially suitable vehicle for the development of a laboratory-scale test. The instrumentation used allowed the relative severities of the original MSHA and large scale tests to be assessed. The conditions of test in the mid-scale gallery were varied as the test programme continued to seek to simulate the performance of belts in the large scale gallery. Thus the results of the tests in the initial phase of the programme of work in the mid-scale facility were used to set the test conditions in the next phase and so on.

This work on varying test parameters and on runs with a re-designed burner and trestle on the three belts used for the large scale tests indicated that the new test conditions chosen were probably an adequate simulation of the conditions in the large scale gallery for the performance of the test belts to be equivalent in the two circumstances.
The work done also indicated that with relatively minor variations, the test conditions chosen could cause all three belts to burn out completely. In relative terms, therefore, the chosen test conditions in the mid-scale gallery were somewhat more severe than those in the large scale gallery.

Tests made to examine the performance of other belt types in the new test arrangement showed that:

- The test is able to distinguish between different qualities of cover on the same carcase.
- The repeatability of the test is good.
- The belt that was not fire-resistant caught fire readily and had to be extinguished.
- The belt that had met the 10 minute test requirements gave similar performance in the new test.
- All of the belts that were tested to represent the complete ranges of those currently accepted for underground use using the High Energy test, performed well in the new test, none recording a length damaged of more than 650 mm.

From these results it was concluded that the new test could be used to simulate performance of belts in the large scale gallery.

5.3 MODIFICATION OF ACCEPTANCE REQUIREMENTS

The acceptance requirements in BC 158 are set out as follows:

either

a) 2250mm left undamaged, or
b) Maximum average temperature rise not exceeding 90 °C, length consumed by weight not exceeding 2000mm and 250mm undamaged, or
c) Maximum average temperature rise of 80 °C, length consumed by weight not exceeding 2250mm and 250mm undamaged

In the absence of a mathematical model relating the two galleries, a pragmatic approach was taken to setting proposed acceptance criteria for the new test.

It is possible to match a) by expressing the damage in terms of the amount of propagation allowable beyond the length over which the burner flames impinge directly on the belt. Using this method the equivalent length undamaged is 500 mm.

To relate the allowable maximum average temperature rise in BC 158 with that in the new test, differences in air flow and fuel consumed and the effect of increased temperatures on propagation must be considered. In terms of the air flow and amount of fuel used temperature rises in the mid-scale gallery should be about 3 times those in the large gallery, giving temperature rises of 270 and 240 °C as equivalent to 90 and 80 °C respectively. However, the limited experience available suggests that temperatures above 170 °C result in complete destruction of the sample. Thus in the restricted environment of the mid-scale gallery, a maximum allowable temperature rise of 170 °C, or somewhat below it, would be more practical. This limit represents a significant tightening of the maximum heat release rate requirement.

On the same basis as length undamaged i.e. from the end of the influence of the burner, for criterion b) the length consumed (by weight) could fall within the length of the MSHA test piece, but for c) this length comes at the end of the sample, and is therefore impracticable. A value for length consumed by weight for the new test would be 1250 mm for criterion b).
Because of the length of the test pieces in the two tests, it is not possible to find an equivalent length undamaged to the figure of 250 mm in criteria b) and c) in the BC 158 requirements. However it was considered that there should be some length of belt remaining undamaged and a figure of 50 mm was suggested for criterion b): criterion c) would have no equivalent.

Following inspection of the results and consultation with both the HSE Project Manager and J H Fenner, it was considered that criterion a) could be tightened to 600 mm. Similarly it was considered that the temperature rise figure for criterion b) could be reduced to a level such that one of the chosen belts, Belt B, would be a marginal failure. The following agreed acceptance criteria are proposed:

Either
a) >600 mm of belt undamaged with no maximum temperature requirement, or
b) >50 mm left undamaged, maximum temperature rise in the duct of 140°C and a maximum length consumed by weight of 1250 mm.

Two runs to be made on each belt type if covers are of equal thickness and 3 runs if they are not, with the third run being a repeat of the worse of the first two.

6 DISCUSSION

The three principal objectives of this research programme were to:

- Characterise the large scale gallery
- Identify, characterise and develop small scale tests
- Seek to understand the importance of changes in test conditions

6.1 CHARACTERISATION OF LARGE GALLERY

A full characterisation of the large gallery has been provided in terms of:

a) air velocity distributions across the gallery cross section at three air speeds,
b) the relationship between the mean air velocity and the differential pressure in the exhaust duct
c) the response of the gallery to known heat inputs, and
d) the performance of three different types of conveyor belt.

From the additional instrumentation used it was evident during this work that there were problems with the control of the large gallery. It is not known to what extent these problems were inherent in the gallery design and to what extent they were a result of the age of the installation.

6.2 SMALL SCALE TESTS

The modifications that were made progressively to the MSHA set up resulted in a test that appears to correlate well with the large scale test. However, the lack of extensive sets of data or previous results on a wide range of belts prevented a more detailed and truly quantitative correlation being established. Time constraints prevented the further exploration of the effect of heat input rate and the distance of the burner below the sample, which also affects the actual heat input to the belt. However, from the success of the correlation achieved in the test programme it appears that belt performance is not very sensitive to heat input rate as long as the surface temperatures down the sample remain similar to those in the large scale test.
6.3 CHANGES IN TEST CONDITIONS

Whilst the brevity of the test programme limited the extent to which test conditions could be varied, there was sufficient variation in the test programme carried out for a number of useful observations to be made:

- Increasing air velocity in the large scale gallery caused increasing damage to the belt sample for the same heat input and set up geometry.
- The capacity of the belt to absorb heat is an important factor in resistance to propagation.
- The extent of propagation is not very sensitive to the rate of heat input in the large gallery.
- In the mid-scale gallery, almost doubling the heat input rate caused a relatively small increase in propagation.
- Changes to the burner geometry and the degree of restraint of the belt sample appear to be significant.
- The performance of belts is much more sensitive to the way in which the heat attacks the belt than the magnitude of the heat input.
- The fact that it is possible to get the “wrong” answer in terms of belt performance by changing burner geometry is important in terms of relating performance in laboratory tests to performance in service situations. In this context the geometry in which the burner is situated beneath the belt is a better simulation of a typical belt fire underground due to a failed idler than is the original MSHA burner geometry.

7 CONCLUSIONS

1. The project has satisfactorily achieved the first of the objectives by characterising the large scale gallery in terms of:
   (a) air velocity distributions across the gallery cross section at three air speeds,
   (b) the relationship between the mean air velocity and the differential pressure in the exhaust duct
   (c) the response of the gallery to known heat inputs, and
   (d) the performance of three different types of conveyor belt.

2. The project has identified, characterised and developed a small scale test based on the MSHA mid scale gallery that adequately simulates the performance of the large scale gallery.

3. A new test method has been provided, together with drawings of the apparatus needed and proposed acceptance levels in Appendix A of the report.

4. The work done has provided important insights into the factors that affect fire propagation on conveyor belts, the most important of which appears to be that changes to the burner/belt geometry relationship can cause significant changes in propagation performance because of changes in the heat distributions.

5. The report provides a history of the development of fire propagation tests used for the acceptance of conveyor belts for use in underground mines and a review of recent work carried out that has been relevant to the project and that underpins the development of the new test.
1 INTRODUCTION

Conveyor belts are widely used for transporting minerals in mines as well as in many other industrial situations. They have a carcase of woven polymeric material or steel cords to provide strength, and covers of rubber or other polymeric materials to give wear resistance and appropriate frictional properties. Because they contain large amounts of polymeric materials their use in certain environments, especially coal mines, but also in steel works, power stations and other enclosed areas must be controlled to minimise the fire risk. It is understood that in the last six years there have been sixty fires in underground mines in the UK alone and that of these, half have been associated with conveyors.

In response to disasters such as that at Cresswell mine in 1950, when 80 people were killed, tests have been developed which belts must pass to be accepted for use in safety-critical situations. For underground mines, with which this report is principally concerned, the fire-resistance tests are the same for textile carcase and steel cord belts. They are contained in BS 3289:1990 [1] and the technically identical British Coal Specification 158:1989 [2] for textile carcase belts and in British Coal Specification 730:1989 [3] for steel cord belts. Conveyors typically consist of a drive mechanism with drive rollers which may be about one metre in diameter and an endless belt which is supported every one to two metres by non-driven rollers called idlers, that can be 100 to 200 mm in diameter. In a mine tunnel, one of the most likely cause of conveyor fires is idlers, overheated either because of failed bearings or because of friction against coal dust lying underneath the conveyor. If the belt is ignited, the fire could spread along to the next idler if it does not self-extinguish in the distance between them. The properties which are important in assessing the fire risk are the ease of ignition of the belt, its propensity to cause fire through frictional heating and the extent of fire spread (propagation) along the belt. Acceptance tests are therefore designed to examine these properties. This report is concerned with tests designed to examine the resistance of conveyor belts to the propagation of fire along their length.

The methods of testing conveyor belting for resistance to propagation have been intended to replicate fire situations in a coal mine by introducing a heat source and measuring the extent to which the fire has caused damage at the end of the test. Four different types of conveyor belt fire propagation tests are currently used in the European Union for the acceptance testing of belts for use in coal mines. All of these use some kind of simulated mine roadway, known as a gallery, but the tests vary in the length of belt sample, type, intensity and duration of heat source and gallery geometry. Detailed descriptions of the tests are given later in this report.

Cerberus considered that research into current fire propagation testing for conveyor belts was needed for three reasons:

¶ uncertainties about the future availability of the UK propagation testing facility
¶ lack of correlation in the performance of belts in the different methods used for testing in Europe
¶ the lack of a mechanism to update the specifications for conveyor belting used in mines in line with developing technology

1.1 FUTURE AVAILABILITY OF THE UK FACILITY

When the proposal to carry out this research was initially put forward it was known that the facility used in the UK was potentially under threat from two sources. The propagation tests specified involve burning a large amount of polymeric material. In some countries outside Europe, tests of this kind are forbidden by anti-pollution regulations. While this is not at present
the case in the UK, the facility used to carry out the tests was in a built-up area and potentially at risk from environmental pressures. Further to this the facility was operated commercially on a site which was leased from a property development company. The threat to the facility from the site not being commercially viable materialised and the facility closed at the end of September 2000.

The loss of this facility means that the propagation test in BS 3289:1990 [1] and British Coal Specifications 158:1989 [2] and 730:1989 [3] could not be carried out in the UK. In Europe, France has recently ceased to carry out this type of testing, preferring to use the facilities that exist in the UK, but continuing to require tests to be conducted to their own test specification. While galleries exist in Belgium and Germany their futures are also uncertain and in any case they do not have the temperature measuring facilities needed for the UK test.

1.2 LACK OF CORRELATION

All of the countries in the EC consider that the conveyor belts that they use in mines are safe. However, a comparison exercise carried out under the auspices of the ECSC in the early 1990’s with a view to introducing a European standard test [4 and 5] revealed that belts which met the acceptance requirements in some of the tests failed others, and some belts which performed well in certain tests burned out completely in others. There was therefore a variation in the stringency of the acceptance criteria and an indication that the tests were not necessarily measuring the same properties.

Further work was carried out in the UK following the correlation exercise and the proposal in CEN to work towards a European standard for propagation testing based on the Double Burner test. The objective of the work was to establish whether belts generally used underground in UK coal mines would pass the Double Burner test. One result was of great concern. A belt that passed the High Energy test with greater than 2250 mm undamaged (a “Grade A” pass) and would be considered safe, burned out completely over the full 4 metres of the test piece in the Double Burner test.

The tests currently in use were not designed to be predictive tools; performance in one test cannot reliably predict performance in another. The propane burner tests are standardised test situations rather than simulations of mine fire scenarios. None of the tests can predict what may happen in a real mine fire.

1.3 UPDATING OF SPECIFICATIONS

The specifications used for conveyor belts approvals in UK mines are now ten years old and belts of sizes that are not included in these specifications are in use in mines. Under British Coal the appropriateness of the fire tests in relation to the belts used was reviewed and updated accordingly. For example, the fire propagation test was increased in severity to cater for the heavier belts coming into service. Now, however, the fire tests contained in those specifications have not been re-considered in the light of the developments that have taken place in belt technology and design over the last ten years.

For these reasons, it was concluded that a programme of research was necessary to study the actual processes occurring in the tests, with a view to circumventing the problems outlined above.
2 OBJECTIVES AND METHODOLOGY OF THE RESEARCH

This section sets out the objectives of the research, the methodology, the companies involved and the timings for the programme that were agreed with the Health and Safety Executive (HSE) as a result of the project submission. The work was carried out under HSE Research Strategy Unit contract reference 4167/R04.085.

2.1 OBJECTIVES

The work proposed for this project had three objectives:

- to provide a full characterisation of the test gallery used in the UK for conveyor belt approvals
- to identify, characterise and develop small scale laboratory tests that could be used to examine the behaviour of conveyor belts in the absence of the large scale facility, seeking to correlate performance in these tests with performance in the large gallery
- in view of the differing performances of belts in the various EC propagation tests, to seek to obtain some understanding of the importance of changes in test conditions on the performance of belts currently approved for use in coal mines by testing over a wider range of test conditions

Because of the loss of the fire gallery in the UK it was considered necessary to produce a full characterisation of the performance of the gallery while it was available to

a) provide information to allow investigations into whether methods other than large scale testing e.g. laboratory scale galleries, could be used to examine the propagation of fire along conveyor belts
b) aid decisions on the requirements for fire resistance in the future when the large gallery is no longer available
c) provide information to aid forensic investigations should these be needed in the event of a serious incident involving a belt fire

A subsidiary objective of the work, although not stated in the project proposal, was to provide a method of giving guidance to the mining industry on the means to assess compliance with established industry requirements for fire resistance in the absence of an ability to carry out the long-established propagation test or a laboratory test that would correlate with it.

2.2 METHODOLOGY

2.2.1 Characterisation Of The Gallery

A series of tests was proposed in which detailed measurements would be used to characterise the gallery by providing a wider understanding of the temperature profile in and around the test piece in the gallery.

The findings from a pilot study which examined data from British Coal tests made in the past concerning oxygen depletion and air temperature measurements would be supplemented by

- measurement of downstream air temperature profile as required in BS 3289 and BC 158
- limited oxygen depletion and air flow measurements
- temperature profiles on the belts
The detailed programme of tests included:

- initial calibration runs with known heat inputs using propane burners (but without belt present) at three air speeds (nominally 0.5, 1.5 and 2.5 m/s) to evaluate the response of the gallery to known fire loads
- test runs on a belt known to meet the requirements of BS 3289/BC 158, with test runs at both the standard test conditions and at lower and higher air speeds
- further belt tests at BS 3289/BC 158 standard test conditions to provide a range of performances. The belts proposed were one that is normally supplied to British Steel specification requirements and would be expected to be a marginal failure and one that is not required to be fire resistant and would be expected to be a failure, and
- test runs using the Double Burner test conditions on the belt known to pass BS 3298/BC158 would be included to examine the effect of a different geometry and rate of heat input.

The instrumentation proposed consisted of:

- anemometers to measure the distribution of air flows in the gallery just in front of the test piece and in the exhaust duct
- oxygen depletion measurements in the exhaust duct
- temperature measurement using a grid of 25 thermocouples in 5 x 5 array two metres downstream of the rear end of the test piece
- for all of the conveyor belt tests a pattern of 15 thermocouples attached to the upper surface of the test belts to give data on the flame feedback and rate of travel of the flame front.

This approach was designed to provide not only an adequate characterisation of the gallery but also information for the development of smaller scale tests.

The actual operation of the large scale gallery, which was operated by International Mining Consultants Ltd, was to be carried out by their personnel under the supervision of Cerberus.

2.2.2 Development Of Small Scale Tests

In parallel with the work to characterise the gallery a survey of the information available from previous laboratory scale gallery tests was proposed to be supplemented by further testing in laboratory scale galleries, making similar measurements to those listed above for the full scale gallery and varying the test parameters to simulate the conditions in the large scale gallery obtained from the results of the gallery characterisation. This work was intended to provide the basis for the development of testing in a small scale model gallery that could eventually be used to determine the performance of belts instead of the full scale gallery.

J H Fenner & Co Ltd had agreed to participate in this work by making available their laboratory scale galleries at their premises in Hull. The detailed test programme in the laboratory scale galleries was to a large extent dependent upon the results of the tests made in the Swadlincote gallery and on the initial measurements in the laboratory galleries themselves. However, in essence it would consist of runs to characterise the galleries under known conditions of heat input followed by tests on the belt samples used in the large gallery, in which such factors as rate of heat input, duration of burn, air flow and position of the sample would be varied to seek to simulate the results obtained in the large scale gallery. The testing in the small scale galleries was to be carried out under the direction of Cerberus and with full consultation with the HSE Project Officer.
The timescales originally agreed with HSE were:

Fire Gallery tests, processing of data from gallery testing, research into previous small scale gallery testing, Three months

Small scale gallery tests Six months

Reporting One month

However, the progress of the work was sufficiently encouraging for the project to be extended to cover a wider range of conveyor belts, including examples encompassing the ranges of all of the types used currently underground. The project timing was extended by five months to accommodate this extra testing.


3 PROPAGATION TESTS CURRENTLY SPECIFIED

This section of the report is designed to provide a background to current testing practices and requirements in Europe and information on the development of the UK propagation test. It describes:

- EU fire propagation tests on conveyor belts,
- the UK fire test facility,
- the development of the test used in the UK to examine fire propagation on conveyor belts for underground use, and
- the work done within the EU on harmonisation of fire propagation tests

3.1 EUROPEAN TESTS FOR FIRE PROPAGATION

As mentioned previously there are four different tests currently specified in the EC for the acceptance testing of belts for use in coal mines. All of them use some kind of simulated mine roadway, known as a gallery, but the tests vary in the length of belt sample, type, intensity and duration of heat source and gallery geometry.

The ‘Luxembourg’ propane burner test was introduced in 1974 by the E. C. S. C. Mines Health and Safety Commission (now the Safety and Health Commission for the Mining and Other Extractive Industries), and forms the basis of two other tests that use propane gas as the fuel. Figure 1 gives the general arrangement for the Luxembourg test, showing the position of the belt sample, trestle on which the sample is mounted and the burner. In Belgium and France, textile carcase belts are required to be tested using a version of the Luxembourg test with deliberate damage to the belt before it is tested. The test is carried out in a gallery having a two metre x two metre cross section.

Following the introduction of the Luxembourg test belt constructions became thicker and heavier and more severe tests were thought necessary to ensure that standards of safety were maintained. These tests were developed independently from one another in the different countries, as were the acceptance criteria. For steel cord and aramid carcase belts in Belgium and France the test time was increased and the geometry changed to supply heat to both sides of the belt simultaneously. This test is known as the Double Burner (DB) test. The Double Burner test has two burners, one above and one below the belt sample, which is equidistant between the burners (Figure 2). The UK uses the High Energy test [6] on all types of belt. The arrangement for the High Energy Test is identical to that of the Luxembourg test, but the length of the test piece, the burner time and the quantity of gas used are different. Details of fuel sources, test piece lengths, gallery dimensions and test times are given in Table 1 below.
Figure 1  General arrangement for the Luxembourg Test

Figure 2  The Double Burner
In Germany a simulated underground roadway is used as a test gallery and 300 kg of wood is used as fuel. This test is known as the Brandstrecke test and is applied to all belt types. The arrangement for the Brandstrecke test is shown in Figure 3, from which it is clear that the test differs in many significant ways from those which use propane gas as the source of fuel. Perhaps the most significant of these differences is that in the Brandstrecke test the major source of fuel is the wood rather than the belt, whereas in the propane tests the major source of fuel, potentially at least, is the belt sample itself.

**Figure 3** Brandstrecke test arrangement (after figure 7 in DIN 22 100)
### Table 1
**Comparison of Luxembourg, High Energy, Double Burner and Brandstrecke tests**

<table>
<thead>
<tr>
<th>Test</th>
<th>Luxembourg</th>
<th>High Energy</th>
<th>Double Burner</th>
<th>Brandstrecke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source of fuel</td>
<td>Propane gas</td>
<td>Propane gas</td>
<td>Propane gas</td>
<td>300 kg wood</td>
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<td>Rate of gas consumption (g/minute)</td>
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<td>Exposure period (min)</td>
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<td>Test piece length (m)</td>
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<td>2.5</td>
<td>18</td>
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<tr>
<td>Test piece width (mm)</td>
<td>900 or 1050</td>
<td>900 or 1050</td>
<td>1250 or full width</td>
<td>Full width</td>
</tr>
<tr>
<td>Air speed (m/s)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Arrangement of burner(s)</td>
<td>Single burner below belt</td>
<td>Single burner below belt</td>
<td>Two burners; one above belt and one below</td>
<td>Wood lines roadway over distance of 3m</td>
</tr>
<tr>
<td>Gallery cross-section</td>
<td>2m x 2m square</td>
<td>2m x 2m square</td>
<td>2m x 2m square</td>
<td>3.5m x 2.9m</td>
</tr>
</tbody>
</table>

The acceptance criteria for each of the tests are given in Table 2 below.

### Table 2
**Acceptance criteria for Luxembourg, High Energy, Double Burner and Brandstrecke tests**

<table>
<thead>
<tr>
<th>Test</th>
<th>Acceptance criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luxembourg</td>
<td>Piece of belt left undamaged over full width of sample</td>
</tr>
<tr>
<td>Double Burner</td>
<td>Piece of belt left undamaged over full width of sample</td>
</tr>
<tr>
<td>High Energy</td>
<td>1. Length of belting undamaged over full width of sample shall exceed 2250 mm, or 2. The maximum average temperature rise shall not exceed 90°C and the length of belting consumed shall not exceed 2000 mm and length undamaged shall exceed 250 mm, or 3. The maximum average temperature rise shall not exceed 80°C and the length of belting consumed shall not exceed 2250 mm and length undamaged shall exceed 250 mm.</td>
</tr>
<tr>
<td>Brandstrecke</td>
<td>Propagation to extend not more than 10 metres past fire source</td>
</tr>
</tbody>
</table>
3.2 THE BRETRY FIRE GALLERY

The Bretby Fire Gallery was opened in 1975 to provide a facility for large scale testing to supplement the small-scale conveyor belt tests introduced in the 1950s [7]. This first gallery was later superseded by the gallery in which the present work was done, which had more advanced instrumentation and ventilation control and a fume treatment plant to minimise environmental pollution. The gallery was 2 m high, 2 m wide and 24 m long, with mineral fibreboard walls, and was housed in a building also containing a control room. Air entered the gallery through a duct and left via the fume treatment plant, which included a valve used to control the air speed in the gallery. The control room contained all the controls and measuring instruments and was sealed from the gallery, although it allowed the operator to observe the fire through a window. A symmetrical array of 5 x 5 thermocouples in a plane 6 m behind the leading edge of the belt sample to be tested enabled the temperature of the gases leaving the gallery to be measured. At the time when the report in reference 7 was written, the air speed and the air oxygen content were also measured at the same points. In addition, the air temperature was measured in the inlet duct, at the gallery mouth, near the roof at the far end of the gallery and in the exhaust duct. The air speed was measured in the inlet duct, exhaust duct and at a point in front of the belt test piece. The concentrations of carbon dioxide and carbon monoxide were measured in the exhaust duct, and of oxygen in the inlet and exhaust duct. The atmospheric pressure and the burner on/off status were monitored. In recent years the only parameters measured were the air speed at a point in front of the test piece and the temperature of the gases leaving the gallery: the burner on/off signal was recorded.

3.3 DEVELOPMENT OF THE HIGH ENERGY PROPANE BURNER TEST

3.3.1 Need for High Energy Propane Burner Test

The 10 minute “Luxembourg” Propane Burner test was carried out on all belts intended for use by the National Coal Board following the opening of the original gallery in 1975. However, by 1979 the thickness of belts being put forward for some applications had increased to the extent where it was suspected that full ignition was not being achieved in the 10 min test. It was thought wise to examine these belts under more severe conditions than those in the 10 minute test.

Accordingly a 26 mm thick steel cord belt was subjected to tests involving propane consumption rates from 130 to 250 g/min and exposure times from 10 to 50 minutes. A longer test piece of 4 m was used to enable the extent of fire damage to be measured; the belt was also judged on the basis of visual examination of the intensity of the fire. It was found in this investigation that the extent of the damage depended on the total mass of gas consumed rather than on the consumption rate alone or the exposure time alone. 7.5 kg of propane was more than sufficient to completely destroy the belt over about 1 m near the burner. The burner appeared to have little influence on the situation once the belt had burned through. As a result of these investigations test conditions for the High Energy Propane Burner test were defined: a comparison of the High Energy and “Luxembourg” tests appears in Table 1 above.

Following this exploratory work experimental test runs using the High Energy (HE) conditions were carried out on both the thicker and thinner belts using the new fire gallery instrumentation.

3.3.2 Test Objectives

The objectives of this fire safety test are firstly to ensure that a conveyor belt does not substantially add to the intensity of a fire, and secondly that fire will not propagate along the belt. Without propagation, the fire, even if it is intense, will be contained. It is therefore of great importance that the belt should not propagate fire. The intention of the fire gallery testing
carried out by British Coal was to examine whether excessive intensity or propagation were likely in a fire under service conditions, having accepting always that the gallery did not necessarily replicate conditions in service which may be less or more conducive to ignition and propagation. However it was supposed that a belt which gives a more or less intense fire on test would give a correspondingly more or less intense fire in service and that a belt which propagates fire on test would be capable of propagating fire in service. It was considered that a greater fire intensity would be expected to cause more propagation; this was confirmed by experience but there were some cases of intense fires with only limited propagation. It was assumed that under slightly different conditions, propagation could have occurred, and that power output, (also referred to as the heat release rate) as measured by the test, should be regarded as a measure of the potential ability to propagate.

3.3.3 Experimental Results

The grand mean, i.e. the mean of all the temperature values from the 5 x 5 thermocouple array, and the percentage depletion in air oxygen content were plotted as a function of time for a belt with ‘acceptable’ fire properties as determined by the 10 minute test. It was found that the grand mean (GM) rose to a peak at about 15 minutes, at which time the belt was almost completely burned through in the area of the burner, then fell back down as the flames died away, reaching a level value where the heating effect was almost completely due to the burner and residual heat in the gallery. This behaviour is illustrated in figure 4, which shows plots of GM temperature against time for both the 10 minute and the HE tests. From this graph it can be seen that the exposure time of 50 minutes is excessive in this case but that the peak value would not have been reached by the end of the 10 minute period specified by the 10 minute test. For some belts, the behaviour in the 10 minute test may give a very inaccurate prediction of the behaviour under more severe conditions; they may pass the 10 minute test but burn out completely with a dangerously high power output in the HE test. In these cases, 10 minutes is not long enough to make this behaviour apparent.

Figure 4  Illustration of difference between High Energy and 10 minute tests.
The plots of oxygen depletion for both the 10 minute and the HE tests gave curves of very similar shapes to the temperature plots, with a peak at the same time value for the HE test.

### 3.3.4 Technical Details Of Testing

The power output may be calculated from either the temperature rise or the oxygen depletion of the exhaust gases. Both of these are measures of the heat release rate, and hence the intensity of the fire. The calculation of the power from the temperature rise or oxygen depletion requires a value for the air speed. Initially this value is uniform and equal to the value imposed upon the system, but as the fire intensity increases, the air speed varies with height, becoming greater near the floor of the gallery and smaller near the roof. In extreme cases, the air speed at the top of the gallery becomes zero or even negative, causing the back-flow of smoke. It is therefore necessary to measure the air speed at the same points as the temperature and to use these values to calculate the value of the power output. However, air speed is very difficult to measure and the problem had not been solved at time that reference 7 was written. Since then, the practice of measuring separate air speeds has been abandoned entirely and the GM temperature rise, rather than the power output, has been taken as one of the pass/fail criteria. The temperature rise is a less direct measure of the power output because of heat loss to the surroundings. Oxygen depletion does not have this disadvantage but requires sensitive and expensive analysers.

The 10 minute test defines “propagation” as the longitudinal extent of any damage to the belt, including minor damage and small blisters due to heat rather than to combustion. Hence it would tend to be an overestimate of the true extent of propagation. It was thought by those developing the High Energy Test more satisfactory to consider propagation in terms of the combustion damage that completely penetrated the belt’s thickness. The test piece was weighed before and after the test, with all brittle and charred material removed prior to weighing. The difference gives the mass of belt consumed, which can be converted to an equivalent length consumed.

It has been argued that the construction of a belt could allow it to propagate fire along the surface without penetration through the belt. In this case the weight loss method would underestimate the length of propagation, so methods of measuring the extent of superficial combustion damage were retained to cope with this situation, should need arise.

The test was terminated when both a period of at least 70 minutes had elapsed since the beginning of the test and a period of at least 10 minutes had elapsed since visible flaming on the test piece or debris had ceased. The test was, however, terminated prematurely if the gallery or equipment were put at risk by the intensity of the fire or if smoke escaped from the gallery entrance.

### 3.3.5 Acceptance Criteria

Acceptance criteria for the HE test were developed [6] after extensive test experience. The assessment of performance was originally by subjective observation of fire intensity but was replaced by objective measurements of power output and propagation. The criteria developed are summarised in Table 2. In addition to the criteria in Table 2 if any test run was terminated prematurely by reason of excessive fire intensity or smoke escaping from the gallery entrance the belt failed to meet the requirements of the specification.

Additional measurements were originally made to support the required measurements, for example oxygen depletion, air speed and additional temperature measurements. Oxygen depletion was at the time considered the most valuable measurement and was under development at the MRDE gallery. However, it involved taking the measuring technology to the limit of current development and was later discontinued.
3.3.6 Reproducibility Of Results

Another fire gallery, belonging to Scandura Ltd., was used to test conveyor belts during the 1980s [8]. Substantial differences were reported between the results from this gallery and the gallery belonging to British Coal so a comparative investigation was carried out, involving the measurement of air speeds, temperature and belt mass loss.

Air speeds were measured without ignition and during fire test runs on the same belt sample. The overall air speed in the MRDE gallery with the burner not ignited was found to be about 20% higher than in the Scandura gallery, but during tests there was a close agreement of air speeds, which could imply a consistent difference or could just be an indication of low reproducibility between tests. (It could, alternatively, mean that during the test the air speed is dominated by the burning rather than by an imposed air flow.)

Temperatures were measured using the standard 5 x 5 thermocouple array. For each gallery, one run was carried out with the burner ignited but without a test piece and two runs with a test piece in position. Temperatures were recorded and plotted for all these runs, and lengths undamaged for those with a test piece.

The temperature rise due to the burner alone was higher in the Scandura than the MRDE gallery. A lower temperature rise was also observed in the MRDE gallery in test runs involving belting, but the length undamaged was virtually the same in each case. It was inferred that the power outputs were the same in each case but the lower air speeds in the Scandura gallery resulted in a larger temperature rise. Examination of some subsequent test results tended to confirm that the air temperature and air speed did not affect the length undamaged. It was concluded that reported differences in test results between the galleries which initiated the test comparisons were due to burners of different powers being used at that time.

3.4 EC WORK ON HARMONISATION OF CONVEYOR BELT STANDARDS

As part of the process of harmonisation of standards for fire propagation testing in Europe [4, 5] comparative tests were carried out with all four of the methods mentioned in 3.1.1. above to examine the extent to which their results agreed.

The comparative tests involved each of the four countries testing samples of belting from the other countries. Each country submitted for testing two samples of conveyor belt typically manufactured in that country for use in coal mines, giving a total of eight belts of different strengths and constructions. Firstly the Luxembourg test was carried out to compare the performances of the testing galleries. The test pieces and design and positioning of the trestle and burner were standardised. Secondly, since there existed a number of minor variations of the Luxembourg test, each country carried out the Luxembourg test with its own modifications. Thirdly each country carried out its own higher-energy test. The three parameters used to measure performance in the tests were length undamaged, length to the flame front, and weight loss.

3.4.1 Comparison Between Galleries

The first comparison, in which all the countries carried out the Luxembourg test, showed variations in the galleries used. The second comparison in which the different adaptations of the test were considered showed less variation than the first. It was of concern that the results from test runs on the same belt in the same gallery could vary considerably. It was considered that the presence of a full width piece of undamaged belting after 10 minutes would be a satisfactory acceptance criterion. More detailed correlation was difficult because of the intrinsic variability of the test.
3.4.2 Local Modifications

The second comparison showed that artificially induced damage, such as holes and areas stripped of their covers, did not increase the test severity significantly in the samples studied.

3.4.3 Higher Energy Tests

Good agreement was found between the French and Belgian Double Burner tests for all the parameters except the length to flame front. The definition of the flame front criterion was not clearly set out before the test, causing difficulties in comparison.

It was found that the higher energy tests gave a different ranking of the belts than the 10-minute burn, suggesting that different properties were being measured in each case. In the higher energy tests the property measured was considered to be probably propagation, whereas in the 10-minute burn, ignition and, in some cases, propagation were measured. It was concluded that the 10-minute burn was a valid test of resistance to ignition, but may not always be valid for measuring propagation.

The French and Belgian double burner tests give good correlation with the UK High Energy test when the length of belt undamaged in the UK test was over two metres. However, differences were found between these tests and the Brandstrecke, with some belts meeting the pass criteria for one test but failing the other. The geometry, heat distribution and method of support are different in the different gallery arrangements and this clearly influences the performance of the belts. The Double Burner test was considered the best test to use as a starting point for a harmonised standard, although it was considered that a longer length of belt than is currently used may be needed in order to determine whether certain belts are self-extinguishing. It was considered that the property of being self-extinguishing would be an adequate criterion for passing a test. In some correlation tests, the length undamaged was zero so it was not possible to determine whether or not the belt would have extinguished itself given a sufficient length.
4 LITERATURE SURVEY

The following sections present the findings from a survey of the relevant literature. They report on:

- basic considerations of fire testing
- flame spread theory and its application to fire performance
- work done in Australia that had similar aims to the present study
- previous work with laboratory-scale tests.

The work included has been selected on the basis of its direct relevance to the objectives set out in Section 2.

4.1 FIRE TESTING AND THE DEVELOPMENT OF FLAME SPREAD.

While the gallery tests were being developed and carried out at the National Coal Board, work was being done in Australia on fire safety testing of conveyor belts for use in coal mines.

The Londonderry Report [9] critically reviews the (then) current fire tests and the knowledge of fire processes, identifies alternative approaches to assessing fire hazards and recommends a research and development programme aimed at introducing a more realistic approach to fire materials hazard assessment.

The Report states that fires had in the past been treated as quasi-steady-state phenomena for the purposes of testing and of mathematical analysis, whereas in reality their behaviour changes over time, going through several stages. Many tests subjected a sample of material to an arbitrary energy source and recorded the result. They may only give the results of one point in a scenario, and might be of little value in predicting behaviour unless the quantity of material and the rate at which it becomes involved in the fire were known. The Londonderry report suggests that the study of the various phases of the development of a fire to give a greater understanding of the dynamics of the situation could lead to the determination of critical events in the process and thus to improvements in the control of fires.

4.1.1 Basic Considerations

The following paragraphs summarise information from the Londonderry report which provides useful background to fire test development and theories of flame spread presented later in this report.

Heating of a polymeric material induces thermal decomposition, releasing gases. The nature and flammability of these gases depends on the composition of the polymer. Low-temperature pyrolysis eliminates functional groups as small molecules, but higher temperatures are required to break most of the chemical bonds in the structure. At still higher temperatures, sufficient gaseous products are formed to give a flammable mixture with oxygen and ignition occurs. Combustion will continue as long as there is a sufficient oxygen supply and a sufficient heat transfer from the flame to the solid material to give an adequate supply of flammable gas.

The time to ignition is controlled by the net energy flux on the surface of the solid material. For ignition to occur, the rate of energy dissipation from the material must be smaller than the rate of energy evolution.

The size of the ignition source is important to fire development. Energy feedback from the flame to the fuel accelerates fire growth exponentially. The growth rate is due to the spreading
of the fire over the first fuel surface initially, followed by spreading to other elements. The point is reached when all of the available fuel surface is involved in the fire and further growth is limited. The fire then proceeds at a relatively constant rate until all of the available fuel is consumed, resulting in decay and extinction.

Heat released is fed back to the pyrolysing surface by convection and radiation. (The larger the flame and the more soot in the flame then the larger is the radiative fraction) leading to increased mass loss and to fire growth. The conduction of heat away from the surface can decrease the rate of pyrolysis, as can re-radiation.

4.1.2 A New Approach To Fire Testing

The Report goes on to consider the various stages in fire development from ignition, through smouldering, flame spread, mass loss during pyrolysis, radiation and soot formation to smoke formation and toxic products. At each stage the authors seek to identify relationships between the parameters that describe the phenomenon taking place.

The report then considers materials behaviour in fires, flammability test methods and mine fire scenarios, before putting forward a new framework for materials testing. The new framework section suggests that the traditional approach to material testing suffers from three significant deficiencies:

- tests must simulate the materials configuration and fire environment.
- scaling effects are a serious problem
- a proliferation of tests to simulate all important configurations and fire environments is needed

The authors suggest experiments that separate the processes taking place during a fire and measure materials characteristics at each component process to produce a model of the whole fire process. The following basic components are suggested:

i. The response of a material to a known radiant heat source is measured in terms of the energy required to ignite the sample under piloted conditions. The external flux is assumed to dominate over convective and radiant feedback. The total energy input to ignition is obtained as a function of input heat flux and serves as a measure of the ignition characteristics of the material

ii. The subsequent rate of heat release of the pyrolysis vapours in response to the imposed heat flux is measured. Ancillary information obtainable could include the rate of release of toxic compounds and the opacity of the plume.

iii. All of these measurements should be obtained over a range of imposed heat fluxes (10 to 80 kW/m²)

iv. The radiant emission characteristics of the burning pyrolysis vapours are measured in such a way that full scale radiation can be predicted.

It is assumed that the necessary measurements can be made in a small scale test and that the results would be dependent only on the material.

The report goes on to discuss these points and expand upon them.
4.2 FLAME SPREAD THEORY

4.2.1 Theoretical Work

Quintiere [10] discussed the application of flame spread theory to identify suitable parameters to characterise the fire performance of materials. In line with the Londonderry Report he argued that current fire performance tests give results that are specific to a given situation but are often applied to predict behaviour in other situations, for which they may not be directly valid. Theoretical equations would provide a basis for analysis of fire test results. Experimental correlations for particular processes, when based on the theory, would give values for the parameters involved. If these parameters remain reasonably constant over an appropriate range of conditions, or correspond to true material properties, they could be considered as ‘effective’ material property values for the processes in question. Test procedures could therefore be developed to measure effective material fire properties, which could then be combined with theory to predict aspects of ignition and fire spread over a wide range of conditions.

In this study, horizontal flame spread under natural convection conditions was considered for many different materials. The diagram below (Fig. 5) illustrates some of the parameters used in the theoretical study of flame spread.

There is a burned-out region up to \( x_b \) in which all the fuel available in the material has been consumed. Pyrolysis occurs between \( x_b \) and \( x_p \) and the flame tip is at a point \( x_f \) with a height \( y_f \). The pyrolysis front \( x_p \) is the point at which the surface temperature is equal to the ignition temperature of the material.

By making suitable approximations and imposing appropriate boundary conditions, an expression for the required temperature rise for flame spread at \( x = x_p \) can be found. This is composed of a contribution from the flame (\( q_f \)) and contribution from the surroundings (\( q_e \)).

For special cases where (\( q_e \)) is only a function of \( x \), and where \( D \) (defined below) is small, or heat losses are ignored or are unimportant with respect to the flame heating component,

\[
T_{ig} - T_i = \frac{2q_f}{\sqrt{D k T_c V_p}} \left( \frac{y_p}{h} - \frac{1}{\text{erfc} \sqrt{\frac{y_p}{h}}} \right)
\]

where:
This, rearranged, gives:

\[ t = \frac{h^2 t}{k \tau c} \]

\[ b = \frac{h^2 (x_f - x_p)}{k \tau c V_p} \]

\[ T_{ig} = \text{ignition temperature (K)} \]

\[ T_u = \text{initial temperature (K)} \]

\[ h = \text{convective heat transfer coefficient (kW.m}^2.K^{-1}) \]

\[ k = \text{thermal conductivity (kW.m}^1.K^{-1}) \]

\[ r = \text{density (kg.m}^3) \]

\[ c = \text{heat capacity (kJ.kg}^{-1}.K^{-1}) \]

\[ t = \text{time (s)} \]

\[ V_p = \text{flame spread velocity (m.s}^{-1}) \]

This equation is used in later papers where it is applied to conveyor belt fire testing.

For pure ignition with a pilot that serves to ignite the flammable mixture, but imparts no heat to the solid, similar results are obtained from a thermal model:

\[ T_{ig} - T_u = \frac{q \dot{h} (x_f - x_p)}{h} \left[ 1 - \exp\left( \frac{h}{T_{ig} - T_u} \right) \right] \]

where: \( T_{ig} - T_u \) is the temperature rise due to the external heating.

This equation is used in later papers where it is applied to conveyor belt fire testing.

These equations give the basic “ingredients” necessary for prediction of flame spread or radiative ignition for materials. Suitable effective materials parameters are the quantity \( k \tau c \), the ignition temperature \( T_{ig} \) and a measure of the flame heat transfer under appropriate conditions. The values \( k \) and \( c \) tend to increase with temperature for solids, and the thermal model ignores
any pyrolysis effect, so the $ktc$ value used must be an effective property, representing some heat loss due to pyrolysis.

The ignition temperature represents the surface temperature required to produce a flammable mixture just at the lower flammable limit for the flow and flame or ignition conditions under consideration. It would be expected to be generally constant over a range of heating conditions. It is difficult to measure the surface temperature at ignition, but it would be possible to infer an effective ignition temperature by determining experimentally the critical radiative heat flux for piloted ignition, using cone calorimetry.

$$q_{flg} = h_e \left( \frac{T_{lg}}{T_u} - 1 \right) + s \left( \frac{T_{lg}^4}{T_u^4} - 1 \right)$$

Where $s$ is the Stephan-Boltzman constant ($5.67 \times 10^{-11}$ kW m$^{-2}$ K$^{-4}$).

$h_e$, the convective heat transfer coefficient, is specific to the conditions of the process in question. The ignition temperature as determined using this equation is the correct ignition temperature required for the thermal models for ignition and flame spread.

4.2.2 Flame Spread Over Horizontal Polymeric Surfaces

Apte et al [11] studied fire propagation across ventilated solid polymeric surfaces with a view to applying their findings to conveyor belts in coal mines. They considered only initial stages of growth; further study was required to model the later stages. The experiments were carried out in a full-scale fire gallery. Sheets of PMMA were ignited on the top surface using a propane torch, which was then removed. The parameters measured were the transient mass loss rate, energy release rate, fire front, pyrolysis length and flame height and length, at various ventilation rates. (Fig. 5) (The experimental conditions are different from those used in European Union tests where the ignition source is present for the duration of the test, and gives a constant heating rate.) The data is analysed on the basis of the theory of Quintiere [10] already discussed.

The flame spreads concurrently with the wind, blowing at a velocity $U_w$. Initial flame spread was observed to be confined within a boundary layer, i.e. a region of flow close to the boundary with the solid surface in which the effects of viscous shear stresses predominate. Later during the propagation, the dominance of buoyancy of the heated air over the horizontal wind force resulted in a plume mode, in which the flame stands up. The transition between the two modes occurred at a pyrolysis length value of approximately 1.2 m, although this value was influenced by the wind speed and was smaller when the wind speed was lower and larger when the wind speed was higher. In the first mode, the spatial average mass loss rate was almost constant and averaged to a value which was higher than the critical extinction mass loss rate for most materials of 4 g m$^{-2}$ s$^{-1}$. In the second mode, the mass loss rate increased continuously, reaching a maximum when the fire had spread over the whole surface.

The flame spread velocity is equal to the rate of advancement of the pyrolysis front, as given by Quintiere’s equation [10]. This equation can also be expressed in terms of a characteristic ignition time $t_i$. Ignition can be considered as a leapfrogging process, *i.e.* a periodic process in which the position of the front at a time $t + t_i$ is given by its position at a time $t$.

If the effective thermal properties, $ktc$ and $T_u$ of the material are known, the spread velocity can be predicted from a knowledge of the flame-to-surface heat flux $q''$ and $(X_f - X_p)$, using Quintiere’s equation. Three independent measurements for the calculation of the heat release
rate were made: oxygen depletion, concentrations of carbon dioxide and carbon monoxide, and the fuel mass loss rate. The greatest deviation between the calculated values was about 17%.

The flame length was plotted against the heat release rate, showing that the flame length increases to an asymptotic value due to the finite length of the fuel sample. A predictive correlation for the flame length in terms of the heat release rate per unit length and the wind speed covering the whole range of data is desired so that the flame spread velocity can be calculated from Quintiere’s equation. Up to a heat release rate corresponding to a flame length of 1 m, there is an approximately linear relationship independent of the wind speed, with a slope in a logarithmic plot of ~ 4/5. Beyond this, in the plume region, a logarithmic plot gives:

\[ x_f \sim (2i\sqrt{U_Q})^{3/4} \]

The correlation in the first regime is purely empirical and does not agree with the theoretical predictions from models postulated in the paper. Trends of the flame spread velocity as predicted from Quintiere’s formula compared well with the flame spread velocity as inferred from the measurements, but correct values of \( kTc \) and \( T_{ig} \) are required for the formula to be tested adequately. The authors state that investigations into the most appropriate values and improved flame length correlation and surface heat flux estimation were under way at time of writing.

The study considered material which has been ignited and then is allowed to burn without any further heat input. This is similar to the later stages of burning in the longer European tests, for example towards the end of the HE test when the belt has burned out over the burner and there is no direct heat input from the burner to the belt. In this case the heat being released from the burning belt is causing propagation of the fire. The difference between the two situations is that in the European tests, the burner remains lit after the belt has ignited. This means that the belt may completely ignite and burn away over the burner as a result of the large heat flux supplied to it, giving a greater initial amount of material burning than in the PMMA tests. After the belt has burned away, the burner continues to release heat into the air for the remainder of the time specified for the test, reducing the heat losses from the belt to the air and maintaining the residual heat at a higher level than would occur if the belt alone were burning. The belt will therefore require less energy input from the burning belt sections to achieve its ignition temperature, since its internal energy is higher than if there were no heat input from the burner. As the flame progresses down the belt, it would be expected that the heating effect of the burner would be less, since the heat would have greater opportunity to rise to the top of the gallery, where its effect on the belt would be smaller due to the increased distance from the belt surface. Eventually a situation identical to that in the PMMA study would be reached, where the effective heating rate of the burner could be considered to be negligible, and propagation is caused by belt-burning alone.

The quantity of heat supplied by the burner also has a marked effect on the initial ignition of the belt; in some tests on National Coal Board conveyor belts, the length of time for which the burner is burning has an effect on the amount of heat released from the belt. (see Figure 4) The slopes of the 10 min and HE tests are the same for the first part of the test, but in the HE test the temperature reaches a peak at around 15 minutes; in the 10 min test the burner was extinguished before this point was reached, indicating that insufficient heat was put into the belt in the 10 min test to reach a critical state of ignition that would allow the belt to reach this peak.
4.3 LABORATORY AND MID-SCALE TESTS

4.3.1 Introduction

Various workers have sought to use small-scale tests, together with the application of predictive models, to either eliminate the need for full-scale testing, or to improve prediction of fire performance, or to do both of these. This part of the literature survey reviews:

- An extensive project aimed at using small-scale test together with predictive methods to eliminate the need for large scale gallery tests on conveyor belts
- Work demonstrating how results from a laboratory-scale test may be used in a predictive model for the assessment of the fire performance of building materials
- Experience with the use of small-scale galleries (mid-scale tests) to provide the information that would be obtained using full-scale galleries.

4.3.2 Australian Study On Conveyor Belt Testing

Despite the introduction of large-scale gallery tests aimed at simulating the conditions in a real fire situation, the incidence of conveyor-belt-related fires remained constant in New South Wales coal mines [12]. It was concluded that current testing methods were inadequate to predict the flammability and fire propagation behaviour of conveyor belts. Correlation exercises were carried out between the current Australian standard Gallery test and two small-scale tests to examine whether the Gallery test could be replaced by a test of this type. Unlike such small-scale tests, the gallery test was labour-intensive, polluting, requires large samples, and only gave limited information.

The objective of the research was to critically review current testing methods, to assess incidences of fires with respect to the current practices in the Australian coal industry, and to correlate the gallery test with the internationally recognised cone calorimeter and FMRC flammability tests (see below for descriptions) using existing fire spread models, using the findings to develop protocols for an improved Australian standard and a risk management strategy, and recommend a quality control test method.

4.3.2.1 Test equipment

Fire Gallery

The Australian gallery test is very similar to the Luxembourg test, with a 100 kW propane burner applied to the sample for 10 minutes to ignite it and an air speed of 1.5 m s^{-1}. The sample is of the width used commercially and is two metres in length. Strips of cover material 50 mm wide are removed in specified positions along the entire sample length on one of the sample surfaces. It is this stripped surface which is exposed to the propane burner. The burner is removed after 10 minutes and the sample allowed to burn out, after which the length undamaged is measured. The pass/fail criterion is based on the length undamaged on the most damaged surface, which should be greater than 250 mm for the belt to pass. Apte et al [12] remarked that this criterion allows fire damage of up to 87.5 % of the sample length. However, this percentage criterion is only valid for test pieces of 2 m in length; unless the fire goes out because of lack of belt material to burn, it would be expected that the same amount of burning would occur in a longer sample than in a shorter sample, neglecting edge effects.

Cone Calorimeter

The Cone Calorimeter test is described in the paper by Babrauskas and Parker [13]. Basically a sample of material approximately 100 mm x 100 mm is subjected to a radiant heat flux that may
be controlled to various levels. The sample may be positioned horizontally or vertically. A spark igniter is used to ignite the pyrolysis vapours. The test measures the ease of ignition, heat release rate and pyrolysis mass loss, and analyses the combustion products. A pass/fail criterion has not yet been introduced for this test, since its method of application for fire property prediction is still under development.

Factory Mutual Research Corporation test

The Factory Mutual Research Corporation (FMRC) test uses apparatus which can be set up to test for ignition or propagation tests. The heat release rate is calculated from the oxygen depletion or from the concentration of carbon dioxide and carbon monoxide in the exhaust gases. The sample burning rate is measured using a load cell. For the ignition test, a 100 mm x 100 mm sample is placed horizontally on a sample holder and subjected to a radiant heat flux. A pilot flame is used as an ignition source, ignition being defined as sustained flaming on the sample surface. The ignition delay time is measured for a range of radiant heat fluxes.

The propagation test uses a 100 mm x 600 mm sample positioned vertically and enclosed inside a quartz tube. The bottom 150 mm is exposed to a radiant flux of 50 kW m\(^{-2}\) and the same type of pilot flame used for ignition. To simulate radiation in large fires, an upward stream of oxygen-enriched air was inserted into the quartz tube. The exhaust gases are analysed.

4.3.2.2 Theoretical considerations of flame spread

The Australian study dealt with the flammability of conveyor belts, which can be measured by the flame spread rate. The criteria measured in the Gallery and FMRC tests are different measures of the flame spread rate. The authors of the Report considered that in a mine conveyor system, the fire spread would be mainly along horizontal or inclined conveyor surfaces, and would be ventilation-assisted.

The equation developed by Quintiere for concurrent flame spread [10] expressed the flame spread velocity as the rate of advancement of the pyrolysis front. The terms in Quintiere’s equation were manipulated to produce parameters describing the material properties and heat release rate i.e. the thermal response parameter (TRP), heat release rate (\(HRR'\)) and to derive the flame propagation index (FPI).

\[
TRP = (T_{ig} - T_0)\left(\frac{k \rho c}{\bar{q}_{\text{rad}} \phi}ight)^{0.5}
\]

\[
\bar{q}_{\text{rad}} = \text{function}(HRR')^n
\]

where the exponent \(n\) depends on the flame geometry, flame size and flame radiation.

A FPI was defined for the FMRC test based on an empirical correlation.

\[
FPI \sim \left(\frac{V_p}{V_p'}\right)^{0.5} = \frac{1000 (c_{\text{rad}} HRR')^{1/3}}{TRP}
\]

where \(c_{\text{rad}}\) is the radiative fraction of chemical heat release rate, assumed to be 0.4 for turbulent fires for most polymeric materials of practical interest.
4.3.2.3 Experimental work and analysis of results

Thirty one belts were tested in the cone calorimeter and gallery tests, and of these, twenty were also tested in the FMRC test. The samples included both new and used belts from a number of manufacturers and were of varying compositions, widths and thicknesses. The report stated that the fire resistance of the belts was mainly due to the covers, which are made of polymeric materials and fire retardants, while the textile carcase material was generally a more flammable nylon material.

The results were analysed in terms of correlations, as defined by the ratio of the number of agreements between different tests to the total number of data points compared. These correlations were found to be good for those belts that convincingly passed or failed, but less good for marginal cases, and there were several belts which passed one test but failed the other.

The Fire Propagation Index (FPI) value was calculated for the Gallery tests from the peak Heat Release Rate (HRR) in the gallery and the Thermal Response Parameter from the Cone tests. The critical value of FPI corresponding to a “pass” in the gallery was determined from a plot of percentage surface damage against FPI. The value determined was FPI $\leq 17$. The FMRC test had a current criterion of FPI $\leq 7$ which is lower in the FMRC than the Gallery test, making the FMRC more stringent. Examination of the data showed that FPI $\leq 17$ for the gallery corresponded to FPI $\leq 15$ for the FMRC test. Possible pass/fail criteria giving a compromise between the gallery and FMRC tests were discussed.

Using HRR and TRP from the Cone tests the correlation between the Cone Calorimeter and the Gallery was found to be worse than that between the FMRC test and the Gallery. The correlation between the Cone and FMRC test using FPI was found to be worse than that between the Cone and the Gallery. Other correlations between the Gallery and various quality control tests, such as the Oxygen Index test were explored.

4.3.2.4 Conclusions

The authors commented on the extent of the correlations and conclude that a full replacement of the Gallery test by an FMRC or Cone Calorimeter test was not justified by their findings.

They also concluded that the Cone Calorimeter did not give a measure of fire propagation as it occurred in the Gallery and FMRC tests. The FMRC test simulated a worst-case scenario more realistically than the Cone tests. In the Cone test, the fire hazard could be underestimated with a sample in a horizontal orientation because the layer of char on the surface protected the carcase from the incident heat. If held vertically, the char could fall off and the sample could burn more vigorously.

The authors further concluded that the current Gallery acceptance criterion could be misleading since it only tested for the extent of fire damage on the surface of the belt. Some belts could fail the test because propagation occurred a long distance along the surface with only a small rate of heat release, while with others the front part of the belt might soften, burn and shrink forward leaving little over the burner. This could limit fire spread and result in a pass despite an initially large heat release rate. They advised that the compliance criteria should also include heat release rate and various parameters associated with the continued integrity of the sample during the test.
4.3.3 Flame Spread Predictions For Building Materials

Goransson and Wickstrom [14] commented that it is important that the results of small scale fire tests should be able to predict behaviour in something like a real fire and that a relationship with an accepted large-scale fire test is established. These authors used results from the Cone Calorimeter to develop a model to predict burning behaviour in the Room/Corner Test (ISO DIS 9705) of materials used for the lining of walls and ceilings in buildings. The model was intended to be used for classification purposes, to be easy to use and to give reasonably accurate results.

In the Room/Corner test an ignition source is placed in the corner of a test room that is lined with the material under test and run at a rate of 100kW for 10 minutes, after which the rate is raised to 300 kW if flashover has not occurred. The authors used two parameters from the Cone Calorimeter test, viz. the time to ignition and the heat release rate curve after ignition. The following two assumptions were used in the model for predicting full scale behaviour:

1. The flame spread rate depends only on the ignition time in the cone calorimeter
2. The heat release rate history at each point in the large scale test is the same as in the Cone Calorimeter.

The flame spread at the start of the Room/Corner test is divided in two parts:

1) The area behind the burner is ignited by the burner flame: the size of this area was assumed to be the same for all materials tested
2) The area burning was assumed to grow exponentially with time if an effective surface temperature was reached, which depended on ignition as well as heat release properties.

The ignition and heat release parameters were obtained from the Cone Calorimeter.

When the burner heat output is raised to 300kW the area burning behind the burner increases and then this area spreads or not depending on the achievement of an effective surface temperature.

4.3.3.1 Rate of heat release and burning area growth

The total heat release was obtained by summing the contributions from the burner and each part of the burning area:

\[ Q_{tot}(t) = Q_{burner} + \sum_{i=1}^{N} D A_i q_{bs} N^4 \]

Where \( D A_i \) is the area incremental the \( i \) th time step and \( N \times \Delta t = t \).

The heat release history \( q_{bs} \) was measured in the Cone Calorimeter. The rate of growth of the area ignited behind the burner was assumed to be proportional to the inverse of the ignition time obtained from the Cone Calorimeter. Further flame spread occurred if the surface temperature just outside the flame area became sufficiently high. The burning area growth was assumed to depend on time as

\[ A(t) = A_0 + at^2/t_{ig} \]
Where $A_0$ is the area behind the burner (equal to 2 $m^2$) and $a$ is a constant empirically determined to be 0.05$m^2/s$.

When the burner output was raised the value of $A_0$ became 5$m^2$ and the value of $a$ became 0.5 $m^2/s$.

4.3.3.2 Criterion for flame spread propagation

Flames were assumed to spread outside the burner area if the surface temperature $Q_s$ was sufficiently high. The surface temperature depended on the temperature of the combustion gases, $Q_g$, and on the thermal response of the surface material. $Q_g$, in turn, depended on the heat release rate from the burner and the burning area in the vicinity of the burner. The area of 2$m^2$ behind the burner was assumed to ignite after a short ignition period.

The gas temperature at an imaginary point at the flame front was assumed to be proportional to the total heat release rate as

$$Q_g = gQ_{tot}^{2/5}$$

$Q_{tot}$ is the sum of the contributions from the burner and the burning wall or ceiling. The proportionality factor $g$ was chosen empirically to give reasonable values to be 50 and 35 $^0K/W^{2/5}$ at the burner rates of 100 and 300 kW respectively.

4.3.3.3 Thermal response of the product

The thermal inertia, $k\tau$, controls the temperature rise of the surface and in the case of constant heat flux this is proportional to the ignition time. The proportionality factor between these quantities was obtained in this work by matching results from wood products. Since thermal inertia is relevant only for semi-infinite products it was replaced in this paper by what was called the Ignition Response value, IRV. By matching with wood products the relationship $IRV=1260.t_i$ was obtained.

The response function of the surface was given by

$$h = Q_s/Q_g = (1-exp((t/t_i).erfc((t/t_i)^{1/2})))$$

Where

$$t = IRV/h^2$$

and the convective heat transfer coefficient $h$ was assumed to be 50 W/m$^2$ K.

For gas temperatures varying with time the surface temperature was given by

$$Q_s(t) = \sum_{i=1}^{N} Q_g^i \cdot h^{N-i}$$

Where $Q_g^i$ is the gas temperature at the i th time increment and $h^{N-i}$ is the response function at time N-i

Using these expressions the surface temperature just outside the flaming area could be calculated and a time-temperature curve constructed.
4.3.3.4 Agreement with experiments

The model was designed with assistance from the results obtained on a series of thirteen products and good agreement was obtained in plots of heat release rate against time.

The model was developed to predict heat release rates in the Room/Corner test from results in the Cone Calorimeter test and to predict whether a product would go to flashover. It included a criterion to predict whether flames would spread beyond the vicinity of the burner. There are obvious parallels with the situation involving the propagation of flame along a conveyor belt.

4.3.4 Use Of Mid-Scale Tests

Two papers that are of particular interest to the present work concern the so-called Mid-Scale tests. These tests involve laboratory-sized fire galleries that are essentially miniature versions of galleries such as that at Swadlincote that has been used in the present work. They are distinguished from small-scale tests by the size of sample used in them and are intended to measure propagation of a fire along a belt rather than some more fundamental property, such as heat release rate, although it may be possible to infer such properties from data obtained in mid-scale tests.

4.3.4.1 German laboratory gallery

Nakagawa et al [15] used a test rig based on the German laboratory gallery described in DIN 22118 [16] to carry out tests on nine different rubber-covered conveyor belts with fabric carcases. The gallery used was 2.5 m long with an opening measuring 0.35 x 0.35 m. Tests were conducted both with the gallery in the horizontal position and with the gallery inclined at 10° to give an upward airflow over the test piece. Two widths of test piece were used, 60mm and 90mm, and for each test thermocouples were positioned along the test piece at intervals of 200mm. The burner used was dimensionally similar to the Franke burner and is situated beneath the test piece approximately 200mm from the end closest to the entrance to the gallery.

These workers used the temperatures recorded by the thermocouples to define an ignition time, \( t_{ig} \), as the time taken for the temperature at a point 200mm downstream of the burner to reach a critical temperature (300°C) and a velocity of propagation, \( V_f \), from the time taken for the critical temperature to travel from the 200mm point to the 1200mm point. The temperature of 300°C was taken as the critical temperature at which the flame front arrived at a particular point on the basis of visual observations.

Whilst most of the discussion in this paper is concerned with comparing the results of these tests with those from small-scale tests such as Limiting Oxygen Index, there are some observations that are useful to the present study. The authors found that the ignition time was longer on the 90mm wide test pieces than on the 60mm wide ones, but the velocity of propagation was greater on the 90mm wide samples than on the 60mm test pieces. This is in line with expectation that the greater mass of the 90mm test pieces would provide more resistance to ignition, but the greater heat release from the 90mm samples would produce higher downstream temperatures which would encourage faster propagation. They remarked that basing a definition of fire resistance on the length of belt damaged seems to be severe and that it might be preferable to measure both ignition time and rate of flame propagation so that the resistance of belts could be classified in more detail.

4.3.4.2 MSHA Gallery

Mintz [17] has made a direct comparison between the performance of belts tested in a 2m x 2m square section gallery, similar to the Swadlincote gallery, and in the mid-scale MSHA gallery.
developed by the US Mine Safety and Health Administration to carry out their so-called BELT (Belt Evaluation Laboratory Test) test.

In the tests carried out in the 2m x 2m gallery the basic arrangement of the trestle, test piece and burner and the rate of gas flow were similar to those described previously for the Luxembourg test. However, for most of the tests the time of exposure to the burner was varied.

The MSHA gallery was 1520mm long and 460mm square in cross section. The belt samples, which were 1520mm long and 229mm wide were positioned on a 220mm high trestle made of perforated angle such that 25mm extended beyond the front of the trestle at the open end of the gallery. The front edge of the sample was positioned 150mm from the end of the gallery, and the flames from the burner impinged on the end of the sample rather than underneath as with the DIN and Luxembourg arrangements. Four thermocouples were installed about 10mm below the roof of the gallery at 250, 600, 910 and 1510mm from the front of the gallery, while a fifth thermocouple was installed in the centre of the duct about 1000mm from the exhaust end of the gallery to provide a measure of the total heat generated. A sixth thermocouple was placed in the middle of the roof about 300mm from the front of the gallery to provide a measure of the heat absorbed by the roof.

Mintz concluded from the results of the tests in the large gallery that the thickness of the belt was important in determining the performance of the belt, with thicker belting more likely to pass the test. In addition, for a series of PVC belts of the same composition, thicker belts tended to reduce the length burned. It was noteworthy that for the other, rubber covered, belts increasing the burner exposure time could lead to propagation over the complete length of the test piece, whereas for one of the PVC belts propagation did not occur even when the exposure time was extended such that the entire region of the belt above the burner was burned away.

The tests made in the MSHA gallery provide a useful background to the present work and Mintz commented extensively on his experience with these tests. The test regime developed by MSHA specifies a standard burner exposure time of five minutes. Mintz varied this exposure time to examine the effect on flame propagation down the belt. For the standard exposure time of 5 minutes, Mintz found that the ratio of damage to top and bottom of the belt was very sensitive to the precise placement of the burner. He additionally commented that his temperature measurements in the roof of the gallery were also very sensitive to the burner position. When a PVC belt that had passed the UK High Energy test, was exposed to a five minute burn the measured temperatures were found to be initially lower than those for the burner alone, indicating absorption of heat by the belt. After a five minute exposure the belt went out quickly, after eight minute exposure the damage was greater, while a ten minute exposure caused the fire to spread the complete length of the sample. This indicates that the MSHA arrangement is capable of causing propagation along a belt considered to be satisfactorily fire resistant for use in UK coal mines, given sufficient heat input.

The thickness of the belt was again found to be an important factor in the performance of belts in the MSHA test with the standard exposure time of five minutes, with thicker belts more likely to pass.

Mintz produced a model in order to obtain a qualitative understanding of the processes taking place in the BELT test. He considered initially the situation without a belt sample and made the following assumptions:

- The walls are perfectly insulating
- The burner heats the flame application zone homogeneously and does not affect the remainder of the chamber
The flame application part of the chamber is completely homogeneous with respect to temperature. The heat capacity of air, the specific volume of air and the air velocity are independent of temperature.

He calculated that with the standard gas flow of methane at the standard air flow rate the rise in temperature of the air should be 81 degrees C, and that 95% of the predicted rise should take place within one second. This rate of temperature rise was predicted by taking small temperature slices and iterating the net heat gain in each slice.

For the situation with a belt sample in place Mintz made the following further assumptions:

- No chemical changes occur in the belt until the minimum ignition temperature is reached
- The temperature of the sample is the same throughout the flame application zone
- The heat capacity of the belt is 750 J kg\(^{-1}\) K\(^{-1}\) and is independent of temperature
- The sample initially absorbs all the heat from the burner, but the air removes some of the heat

If the air were completely effective in removing the heat then the temperature rise would be the same as in the absence of the belt sample, theoretically 81°C, but the time required to reach this temperature would be longer and would depend on the belt mass. Mintz calculated that to achieve a typical minimum ignition temperature, which he quoted as 620 °C, the ventilation was not very effective in removing the heat. He presented a plot of temperature rise against time for belts of various mass and remarked that this plot, while very simplified does illustrate the very large effect of the heat capacity on whether a belt will pass the BELT test.

In the discussion to his paper Mintz concluded that the work showed that the most useful method of ranking relative flammabilities of belts was through the total heat input, which at constant gas flow could be replaced by burner application time. He remarked that the correlation of the BELT tests with large scale propane gallery tests was generally good and went on to discuss the effect of belt thickness, the fact that the MSHA test could fully ignite almost any belt and the differences between the MSHA apparatus and full scale galleries.

This study by Mintz is extremely useful to the present work. It demonstrates that the mid-scale test may be a way forward, but the present authors feel that the work indicates that using a fixed exposure time, as the BELT test does, may not give a proper indication of the ability of a belt to resist propagation since the belt may not actually be fully ignited in five minutes. Equally the use of increasing exposure times may only be giving an indication of the time to ignition, which may not be equated directly with resistance to propagation. In the propagation test given in BS 3289 and British Coal Specification 158 the belt is exposed to what is in effect an infinitely long burner time and is required to limit propagation down the belt to a given amount even if all of the belt over the fire source becomes ignited and the belt itself becomes the major source of fuel.

4.4 COMMENTS

The intention of this literature survey was to draw together relevant work that could be used to support and further the present studies. It has demonstrated that a considerably amount of work and original thinking has taken place on the subject of fire testing of conveyor belting and that good progress has been made in understanding the phenomena taking place in flame propagation. The replacement of large scale gallery testing by smaller tests has been uppermost in much of the work reviewed. It is clear that the predictive work using sophisticated models of flame spread theory with laboratory-scale test results can give qualitative or even semi-
quantitative results, but has not yet been developed to a condition where replacement of large scale testing can be undertaken with confidence. However, the models may be sufficiently accurate to indicate whether gross propagation is likely to occur in given circumstances. The mid-scale laboratory gallery tests appear to be useful tools for evaluating belt performance, but the authors were not convinced that the methodologies adopted give proper representations of larger scale fires and in particular the situation pertaining in the fire propagation test used by the UK to qualify belts for use underground in coal mines. They believed, however, that with suitable investigation and modification mid-scale test arrangements were more likely to yield a replacement for the large scale test than were laboratory scale tests. The work surveyed was drawn upon extensively in the formulation of the test programme and the processing of the data generated here.
5 EXPERIMENTAL WORK

5.1 INTRODUCTION

The experimental work is in two parts. The first part was carried out using the former British Coal large scale fire gallery and the second using the mid-scale MSHA gallery at the premises of J H Fenner and Co Ltd.

Two types of tests were carried out in each gallery:

- Tests to characterise the gallery itself
- Tests to characterise the performances of conveyor belts that were expected to give small, intermediate and large amounts of propagation.

The tests in the large-scale gallery were all made prior to any work being done in the MSHA gallery. The results from the large-scale gallery were used as the basis on which to develop the mid-scale gallery test. All of the work done in the large gallery, the results and their analysis are therefore presented first and are followed by the work done in the MSHA facility. The test conditions in the MSHA gallery were varied as the work progressed in order to try to simulate the performance of the belts in the large-scale gallery.

Severe time constraints were imposed on the large-scale tests. The closure of the gallery and vacation of the site on which it was situated were scheduled for the end of September 2000. Because of staffing problems related to the closure of the IMC operation at Bretby and Swadlincote, work on the setting up of the instrumentation required for the testing did not begin until the beginning of September. This left no opportunity for repeating any of the work in the event of problems with the facility. Equally, because of the closure of the large-scale facility there was no possibility of returning to the gallery after the work in the mid-scale gallery to confirm correlations in performance using additional test specimens.

5.2 LARGE SCALE GALLERY TESTS

5.2.1 Gallery Characterisation

5.2.1.1 Apparatus

The Bretby fire gallery has been described in 3.2 above. Just prior to the present tests the only measurements made in tests carried out in the gallery had been those specified in British Coal Specification 158;

- air velocity at a designated point in front of the test piece,
- the mean exhaust air temperature and
- the burner on time

The air velocity had been measured using a portable anemometer inserted into the gallery through a port in the side wall and removed after the air velocity had been set. The mean air temperature had been measured using the 5 x 5 thermocouple array situated two metres behind the trailing edge of the belt sample. The control system had allowed measurements of all twenty five thermocouples to be made every six seconds and recorded using a data logger. Computer processing of the data to provide the parameters needed for the purposes of Specification 158 had been available.
For the gallery characterisation tests additional instrumentation was installed:

- an array of nine hot wire anemometers placed 0.75 metre in front of the trestle
- an oxygen analyser situated in the centre of the exhaust duct 1.5 metres behind the end of the conical transition piece between the square gallery and the circular duct
- a differential pressure transducer (pitot tube) situated in the duct at the same point as the oxygen analyser probe.

The positions of the anemometers, thermocouples, differential pressure and oxygen probes are shown in Figure 6 below

![Figure 6](image)

**Figure 6** Positions of anemometers, thermocouples and differential pressure and oxygen probes

Figure 7 below shows the arrangement of anemometers, thermocouples trestle and burner in the gallery as seen from the entrance.

The purpose of the array of anemometers was to check the air flow distribution across the gallery section, both prior to and during a fire. The anemometers were calibrated initially using the portable anemometer positioned adjacent to each of the fixed anemometers in turn by inserting it through the port in the gallery side.

The oxygen analyser and differential pressure probes were installed to provide a measure of the powers of the test fires by oxygen depletion for comparison with the power calculated from the mean air temperature and the gas consumption. It would have been preferable to measure oxygen levels at the same twenty five points as the temperature, as was done when the gallery was originally constructed. However insufficient analysers were available for this at the time this work was carried out.
A data logger recorded the air velocity, differential pressure and oxygen level data every ten seconds.

Two propane gas burners, complying with the requirements of British Coal Specification 158 were available to provide standard heat sources. Flow to one burner was controlled through a valve and a pressure gauge was used to regulate the quantity of gas consumed. Flow control equipment was not available for the second burner but a pressure gauge was available. Quantities of gas used were measured by weighing the gas bottles before and after the tests.

![Figure 7](image)

**Figure 7** View of Anemometers, thermocouples, trestle and burner in large scale gallery

### 5.2.1.2 Tests

Four test runs were made.

In the first three, made at nominal air velocities of 0.5, 1.5 and 2.0 metres per second, the intention was to simulate the situation occurring typically in a fire test on a belt that would pass the requirements of Specification 158. In such a test, the heat output is initially only from the burner under the belt, the belt then catches fire and contributes to the heat release rate. It subsequently ceases to burn, leaving only the propane burner alight. Two burners were used in these tests, the first in the position required by Specification 158 below the trestle and the second positioned on the trestle. The first burner under the trestle was lit, allowed to burn for a time, the second burner was lit, allowed to burn for a period then extinguished and the first burner was left burning for a further period. In each test air velocity was set using the portable anemometer and values of all parameters were recorded for a period prior to lighting the first burner through the port in the side wall. All measurements were continued after both burners had been extinguished in order to capture the “run down” data. The following table shows the times for which each of the burners was lit in each of the three tests.
Table 3
Burner times during simulated belt burn tests

<table>
<thead>
<tr>
<th>Nominal air velocity (m/s)</th>
<th>First burner lit (min)</th>
<th>Second burner lit (min)</th>
<th>Second burner off (min)</th>
<th>First burner off (min)</th>
<th>Total burn time first burner (min)</th>
<th>Total burn time second burner (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0</td>
<td>15</td>
<td>22</td>
<td>29.5</td>
<td>29.5</td>
<td>7.0</td>
</tr>
<tr>
<td>1.5</td>
<td>0</td>
<td>15</td>
<td>30</td>
<td>40</td>
<td>40</td>
<td>15</td>
</tr>
<tr>
<td>2.0</td>
<td>0</td>
<td>15</td>
<td>30</td>
<td>45</td>
<td>45</td>
<td>15</td>
</tr>
</tbody>
</table>

In the fourth test only the burner under the trestle was used and was allowed to burn for a period of fifty minutes. This test was made at a nominal air velocity of 1.0 m/s and the intention in carrying out this test was to determine the rate at which the temperature of the exhaust air stabilised over the normal period of a test to Specification 158.

5.2.2 Conveyor Belt Fire Tests

5.2.2.1 Belts tested

Due to the limited time available only a modest programme of tests involving burns on three types of conveyor belt was possible. As indicated above the three belts were selected to give differing performances in the propagation tests:

- A belt that would readily pass the Specification 158 test (designated Belt A in Table 4 below)
- A belt that would give an intermediate amount of propagation, resulting in a “marginal” result in the Specification 158 test (designated Belt B in Table 4)
- A belt that would give extensive propagation and be expected to fail the Specification 158 test (designated Belt C in Table 4)

The following table provides details of the three belts tested.

Table 4
Details of belts tested

<table>
<thead>
<tr>
<th>Code</th>
<th>Construction</th>
<th>Thickness (mm)</th>
<th>Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Solid woven PPe 1750 N/mm PVC impregnated 1/1 PVC covers 15.2 kg/m²</td>
<td>12.5</td>
<td>1050</td>
</tr>
<tr>
<td>B</td>
<td>Solid woven EePe 490 N/mm rubber impregnated 4/1.5 rubber covers 9.8 kg/m²</td>
<td>8.5</td>
<td>1050</td>
</tr>
<tr>
<td>C</td>
<td>Solid woven EbPe 875 N/mm PVC impregnated 2/2 rubber covers on 1/1 PVC 16.5 kg/m²</td>
<td>14</td>
<td>1050</td>
</tr>
</tbody>
</table>

Note: All of the test pieces were nominally four metres long.
5.2.2.2 Apparatus

Certain changes were made to the apparatus used for the gallery characterisation tests. Firstly, the array of anemometers was reduced to leave only the central three. This was necessary to allow access for the installation on and removal from the trestle of the conveyor belt samples. Secondly, fifteen K-type thermocouples were attached by stapling them to the surface of the belts being tested when the belt sample was in situ on the trestle. The pattern of thermocouples is shown in Figure 8 below. The positioning of the thermocouples shown on the left in Figure 8 was changed after the first test to provide better data capture, and that shown on the right was used for all subsequent tests. Temperatures were recorded from all fifteen thermocouples every ten seconds using a data logger. The remainder of the apparatus was as for the tests to characterise the gallery.

Figure 8 Positions of belt thermocouples for test A1 (left) and the remainder of the belt tests (right)

A typical arrangement of thermocouples in Belt A is shown in figure 9 below.
5.2.2.3 Conveyor belt tests made

The intended programme of tests in the large-scale gallery was as follows:

- Duplicate tests on each of the three belts under the conditions specified in British Coal Specification 158 to generate detailed information on the progress of different sized belt fires.
- Duplicate tests on a belt that would pass Specification 158 (Belt A) at 0.5 m/s and 2.5 m/s nominal air velocities to examine the effect of air velocity on propagation.
- Duplicate tests on a belt that would pass Specification 158 (Belt A) using the double burner geometry to investigate the effect of changing the heat input configuration and rate.

The actual programme carried out differed from that intended in the following ways:

- In all of the tests the gas flow to the burner under the belt was lower than specified in Specification 158. Actual values were approximately 5.5 kg compared to the specified 7.5 kg in fifty minutes. The reason for this is not clear but is probably associated with a fault in the flow control mechanism. No time was available to investigate this problem.
- In the first test at 0.5 m/s air velocity it was clear within the first few minutes of the test that the air flow in the gallery was insufficient to clear the smoke, which was backing up against the air flow and starting to emerge from the front end of the gallery. A dangerous situation could have arisen had the test been allowed to continue. The lowest air velocity was therefore changed to 1.0 m/s.
- An additional test at nominally Specification 158 conditions was made using the test piece that had been used for the aborted 0.5 m/s air flow test.
- The maximum air velocity that could be achieved was 2.1 m/s.
- Only one Double Burner test was made. In this test the total gas used by each burner should have been 2.6 kg, but the lack of control of the gas flow to the top burner meant that this was exceeded.

The following table summarises the test programme.

---

**Figure 9** Thermocouples attached to sample of Belt A

---
Table 5

Conveyor belt fire propagation tests made

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Nominal Test Specification</th>
<th>Burner on time (min)</th>
<th>Air velocity (m/s)</th>
<th>Gas used (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>BC 158</td>
<td>50</td>
<td>1.47</td>
<td>5.4</td>
</tr>
<tr>
<td>A2</td>
<td>BC 158</td>
<td>50</td>
<td>1.51</td>
<td>5.4</td>
</tr>
<tr>
<td>A3</td>
<td>BC 158</td>
<td>50</td>
<td>1.5</td>
<td>5.5</td>
</tr>
<tr>
<td>A4</td>
<td>BC 158 with high air flow</td>
<td>50</td>
<td>2.1</td>
<td>5.65</td>
</tr>
<tr>
<td>A5</td>
<td>BC 158 with low air flow</td>
<td>50</td>
<td>2.1</td>
<td>5.4</td>
</tr>
<tr>
<td>A6</td>
<td>BC 158 with high air flow</td>
<td>50</td>
<td>1.0</td>
<td>5.3</td>
</tr>
<tr>
<td>A7</td>
<td>BC 158 with low air flow</td>
<td>50</td>
<td>1.48</td>
<td>5.1</td>
</tr>
<tr>
<td>B1</td>
<td>BC 158</td>
<td>50</td>
<td>1.47</td>
<td>5.1</td>
</tr>
<tr>
<td>B2</td>
<td>BC 158</td>
<td>50</td>
<td>1.47</td>
<td>5.1</td>
</tr>
<tr>
<td>C1</td>
<td>BC 158</td>
<td>50</td>
<td>1.49</td>
<td>5.6</td>
</tr>
<tr>
<td>A8</td>
<td>Double Burner</td>
<td>20</td>
<td>1.49</td>
<td>2.2 lower burner 4.6 upper burner</td>
</tr>
<tr>
<td>C1</td>
<td>BC 158</td>
<td>50</td>
<td>1.5</td>
<td>5.2</td>
</tr>
</tbody>
</table>

The tests on belt B were made with the thicker cover downwards.

5.3 RESULTS OF LARGE-SCALE GALLERY TESTS

5.3.1 Gallery Characterisation Tests

The three parameters to be reported on here are air flow, temperature and oxygen depletion.

5.3.1.1 Air flow

The following tables show values of air velocity for each of the nine anemometers under three conditions:

- Initially after the air velocity had been set
- After the first burner had been lit and values had stabilised
- After the second burner had been lit and values had stabilised

Each of the values shown is the mean air velocity at that position taken over a period of time during which the air velocity was judged to be stable. R 1 indicates the top row situated 0.5 m below the roof of the gallery and C 1 is the left hand column. The tables show also the row and column averages and the overall average (Grand mean).

Table 6

Air velocity distributions (m/s) with velocity set at 0.5 m/s

<table>
<thead>
<tr>
<th></th>
<th>No burner</th>
<th>First burner</th>
<th>First and second burners</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C 1</td>
<td>C2</td>
<td>C3</td>
</tr>
<tr>
<td>R 1</td>
<td>0.65</td>
<td>0.66</td>
<td>0.64</td>
</tr>
<tr>
<td>R 2</td>
<td>0.53</td>
<td>0.54</td>
<td>0.52</td>
</tr>
<tr>
<td>R 3</td>
<td>0.48</td>
<td>0.33</td>
<td>0.35</td>
</tr>
<tr>
<td>C. Av.</td>
<td>0.55</td>
<td>0.51</td>
<td>0.50</td>
</tr>
<tr>
<td>Grand mean</td>
<td>0.52</td>
<td>0.53</td>
<td></td>
</tr>
</tbody>
</table>
Table 7  Air velocity distributions (m/s) with velocity set at 1.55 m/s

<table>
<thead>
<tr>
<th></th>
<th>No burner</th>
<th>1st burner</th>
<th>1st and 2nd burners</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1, C2, C3</td>
<td>R av, C1, C2, C3, R av</td>
<td>C1, C2, C3, R av</td>
</tr>
<tr>
<td>R 1</td>
<td>1.47, 1.49, 1.21, 1.39</td>
<td>1.38, 1.40, 1.14, 1.31</td>
<td>1.62, 1.18, 1.66, 1.49</td>
</tr>
<tr>
<td>R 2</td>
<td>1.43, 1.43, 1.27, 1.38</td>
<td>1.41, 1.34, 1.20, 1.32</td>
<td>1.95, 1.55, 1.49, 1.66</td>
</tr>
<tr>
<td>R 3</td>
<td>1.46, 1.56, 1.39, 1.47</td>
<td>1.35, 1.46, 1.31, 1.37</td>
<td>1.61, 1.84, 1.54, 1.66</td>
</tr>
<tr>
<td>C, Av.</td>
<td>1.45, 1.49, 1.29</td>
<td>1.38, 1.40, 1.22</td>
<td>1.73, 1.52, 1.56</td>
</tr>
<tr>
<td>Grand mean</td>
<td>1.41</td>
<td>1.33</td>
<td>1.60</td>
</tr>
</tbody>
</table>

Table 8  Air velocity distributions (m/s) with velocity set at 2.15 m/s

<table>
<thead>
<tr>
<th></th>
<th>No burner</th>
<th>1st burner</th>
<th>1st and 2nd burners</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1, C2, C3</td>
<td>R av, C1, C2, C3, R av</td>
<td>C1, C2, C3, R av</td>
</tr>
<tr>
<td>R 1</td>
<td>2.04, 2.17, 1.69, 1.97</td>
<td>2.07, 2.19, 1.70, 1.99</td>
<td>2.16, 2.31, 1.76, 2.08</td>
</tr>
<tr>
<td>R 2</td>
<td>2.15, 1.98, 1.81, 1.98</td>
<td>2.20, 1.97, 1.81, 1.99</td>
<td>2.34, 1.90, 1.77, 2.00</td>
</tr>
<tr>
<td>R 3</td>
<td>1.99, 2.33, 2.01, 2.11</td>
<td>1.99, 2.36, 2.01, 2.12</td>
<td>1.92, 2.38, 2.02, 2.11</td>
</tr>
<tr>
<td>C, Av.</td>
<td>2.06, 2.16, 1.84</td>
<td>2.09, 2.17, 1.83</td>
<td>2.13, 2.20, 1.85</td>
</tr>
<tr>
<td>Grand mean</td>
<td>2.02</td>
<td>2.03</td>
<td>2.06</td>
</tr>
</tbody>
</table>

As noted above a fourth test was carried out at a nominal air velocity of 1.0 m/s over a duration of fifty minutes. For this test only the centre column of anemometers was available. The table below shows the results.

Table 9  Air velocity distributions (m/s) with velocity set at 1.01 m/s

<table>
<thead>
<tr>
<th></th>
<th>No burner</th>
<th>1st burner</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1, C2, C3</td>
<td>C1, C2, C3</td>
</tr>
<tr>
<td>R 1</td>
<td>1.43, 1.25, 1.50</td>
<td>1.39, 1.42</td>
</tr>
<tr>
<td>R 2</td>
<td>1.25, 1.56, 1.50</td>
<td>1.26, 1.56</td>
</tr>
</tbody>
</table>

There are six points to note from these results:

1) At a nominal velocity of 0.5 m/s the air velocity distribution prior to the first burner being lit is very unequal, with substantially higher values at the top of the gallery.

2) The air velocity distribution upstream of the burners changes substantially at 0.5 m/s when the burners are lit. The readings from the top row of anemometers changed in a manner consistent with the air velocity becoming negative in this region, although the readings themselves did not, of course become negative.

3) At 1.55 and 2.15 m/s the air velocity distributions from top to bottom of the gallery before the burners are lit are quite even, but there appears to be a lower air velocity at the right hand side of the gallery.

4) The air velocity distribution upstream of the burners changes little at 1.55 and 2.15 m/s when the burners are lit.

5) The measured values of air velocity in the fourth test are in conflict with the nominal air velocity which was set at 1.01 m/s, giving values around 1.4 m/s. The only explanations that can be offered for this is that the air velocity set by the portable anemometer was incorrectly noted or that the calibrations of the fixed anemometers had drifted substantially. This point is explored later.
6) The air velocity distribution at the nominal 1.01 m/s changes little when the burner is lit.

5.3.1.2 Temperatures

A composite plot of the grand mean temperature rises against time is shown in Figure 10. There are several features of this figure that are noteworthy:

- The graphs for air velocity of 0.5, 1.55 and 2.15 m/s are still rising at the end of the first fifteen minutes when only the first burner was lit.
- The graph for the nominal air velocity of 1.01 m/s is still rising at the end of fifty minutes.
- The graph for the nominal air velocity of 1.01 m/s falls close to that for 1.55 m/s, suggesting that the air velocity for this run was actually 1.4 m/s as shown by the fixed anemometers.
- The temperature rise for the second burner did not follow the same form as that for the first burner. This burner had no flow control valve and the pressure was seen to fall during the periods when this burner was on, indicating that the flow rate, and hence the heat input, fell from an initial high value.

![Figure 10 Calibration runs: Grand mean temperature v time](image)

Parameters have been extracted from these data for estimation of the heat release rates by the temperature rises of the air for comparison with those from oxygen depletion and quantity of propane used.

5.3.1.3 Oxygen depletion

A composite plot of the oxygen depletion percentages against time is shown in Figure 11. There are several features of this figure that are noteworthy:

- In the graphs for air velocities of 0.5, 1.55 and 2.15 m/s the oxygen depletion does not return to zero after the burners are turned off, neither do the values return to their previous levels after the second burner is turned off.
- The graph for the nominal air velocity of 1.01 m/s shows a marked hunting.
- The graph for the nominal air velocity of 1.01 m/s falls between those for 0.5 and 1.55 m/s.
The oxygen depletion levels while the second burner is alight in the tests at 1.55 and 2.15 m/s fall off from an initial high value, indicating that the heat release rate, and hence the propane consumption rate was changing during these periods.

The absolute values of oxygen depletion, particularly at the higher air velocities, are small, while the scatter in the values is relatively large.

Despite these difficulties, parameters have been extracted from the data for the calculation of heat release rates by oxygen depletion.

5.3.2 Conveyor Belt Tests

The instrumentation in place for the tests on the three types of conveyor belts was intended to provide data from which the progress of the fires could be followed from

- the 5 x 5 thermocouple array positioned 2 m behind the belt sample
- the 15 thermocouples attached to the belt surfaces.

Oxygen depletion measurements

In addition the measurements of physical damage required by BS 3289 and BC 158 are presented here. To aid the interpretation of the temperature measurements in terms of the physical damage to the belts the two types of measurement are presented in the same section.

5.3.2.1 Temperature and damage measurements

From the outputs from the thermocouple arrays, plots of the grand mean air temperature and the temperatures along the belts as the fire progressed could be produced. The latter could be further processed to provide temperature distributions down the belt at specific time instants, for each of the two rows of thermocouples (“odds” and “evens”). Typical plots are shown in Figures 12, 13 and 14 for Belt A. The time that the burner was lit has been taken as the zero time point. In

Figure 11. Calibration runs: Oxygen depletion v time

![Figure 11. Calibration runs: Oxygen depletion v time](image-url)
Figure 12 The legend indicates the distances of the thermocouples from the leading edge of the belt sample.

**Figure 12** Plot of grand mean air temperature v time for Belt A at 1.5 m/s air velocity

**Figure 13** Plot of “even” belt thermocouple temperatures v time for Belt A at 1.5 m/s air velocity
In figure 12 the mean temperature rises to a small peak at about four minutes, declines slightly and then rises at a rather slower rate. During this initial period Belt A distorts over the burner, deflecting upwards to form a ridge, which allows the burner flames to impinge on the front edge of the sample, which subsequently flattens again. Some burning of the front edge of the belt takes place before the sample burns through and becomes fully alight. The temperature in this figure peaks at around 21 minutes, which coincides with the peaks in figure 13. In figure 12 the temperature levels out after 40 minutes, indicating that the fire on the belt has gone out and that only the burner and the residual heat in the belt and gallery structure are contributing to the temperature rise.

It is clear from Figure 14 that it is possible to determine the rate of travel of the fire down the belt, and this was done for all of the tests made and is reported below.

The performances of the belts differed widely. In none of the tests on Belt A did the fire propagate beyond the belt thermocouples, but for belts B and C propagation was more rapid and extensive and continued past the furthermost thermocouple positioned at two metres from the leading edge of the belt sample. For belt C propagation along the rubber cover was considerably greater than along the textile carcase of this belt. Figure 15 illustrates both the measurements of damage and the ways in which belts A, B and C were damaged. It was observed that during the burns thermocouples occasionally became detached from the belt surfaces before the belt had burned away at the thermocouple tips. Naturally all of the thermocouples became detached when the flame front had moved past their respective positions and destroyed the surface at that point. Figure 16 shows mean air temperature against time for all three belts at 1.5 m/s nominal air velocity. The difference in performance of the belts is clear. However it should be noted that both belts B and C self extinguished and the test pieces were not completely consumed.
Figure 15  Damage and measurements on Belts A, B and C
The measures of damage required by British Coal Specification 158 were made on the belts and are presented below in Table 10. Taking these measures of damage and the temperature rise data Belts A and B would have met the propane burner test requirements in Specification 158, while belt C would have failed on the temperature rise criterion.

In table 10 the length damaged is shown for ease of comparison with the positions of the belt thermocouples. These figures have been derived by subtracting the lengths undamaged from the original belt lengths. The lengths to the flame front and the lengths to penetration are also shown on the same basis, i.e. from the burner end of the belt. Since the belt samples were not all exactly 4000 mm in length the sum of the lengths damaged and undamaged does not necessarily add up to 4000 mm.

**Table 10** Measures of belt damage

<table>
<thead>
<tr>
<th>Test No</th>
<th>Length undamaged (mm)</th>
<th>Length consumed by weight (mm)</th>
<th>Length damaged (mm)</th>
<th>Length to flame front (mm)</th>
<th>Length to penetration (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>A1</td>
<td>2590</td>
<td>2530</td>
<td>765</td>
<td>1395</td>
<td>1455</td>
</tr>
<tr>
<td>A2</td>
<td>2860</td>
<td>3030</td>
<td>601</td>
<td>1160</td>
<td>990</td>
</tr>
<tr>
<td>A3</td>
<td>1920</td>
<td>2000</td>
<td>777</td>
<td>2060</td>
<td>1980</td>
</tr>
<tr>
<td>A4</td>
<td>2440</td>
<td>2470</td>
<td>1040</td>
<td>1556</td>
<td>1526</td>
</tr>
<tr>
<td>A5</td>
<td>2180</td>
<td>2150</td>
<td>1253</td>
<td>1810</td>
<td>1840</td>
</tr>
<tr>
<td>A6</td>
<td>1820</td>
<td>2220</td>
<td>1199</td>
<td>2210</td>
<td>1810</td>
</tr>
<tr>
<td>A7</td>
<td>2650</td>
<td>2890</td>
<td>843</td>
<td>1320</td>
<td>1080</td>
</tr>
<tr>
<td>B1</td>
<td>1700</td>
<td>1870</td>
<td>1721</td>
<td>2300</td>
<td>2130</td>
</tr>
<tr>
<td>B2</td>
<td>1710</td>
<td>1820</td>
<td>1904</td>
<td>2280</td>
<td>2170</td>
</tr>
<tr>
<td>C1</td>
<td>910</td>
<td>1450</td>
<td>1709</td>
<td>3050</td>
<td>2510</td>
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<tr>
<td>A8</td>
<td>1830</td>
<td>2190</td>
<td>1315</td>
<td>2210</td>
<td>1850</td>
</tr>
<tr>
<td>C2</td>
<td>540</td>
<td>1080</td>
<td>1986</td>
<td>3550</td>
<td>3010</td>
</tr>
</tbody>
</table>

**Figure 16** Grand mean air temperature rises for Belts A, B and C at nominal 1.5 m/s air velocity
5.3.2.2 Oxygen depletion

It was noted in Section 5.3.1.3 above that the response of the oxygen analyser was problematic during the calibration tests. During the conveyor belt tests the response of the oxygen analyser appeared to have deteriorated and was so small during these tests that it was generally masked by the regular “hunting” evident in the plots of oxygen level against time. The accuracy of these data was insufficient to allow satisfactory values to be extracted from them.

5.4 ANALYSIS OF LARGE-SCALE GALLERY RESULTS

5.4.1 Gallery Characterisation

From the results of the characterisation tests it was possible to derive various relationships that are useful for understanding how the large gallery might relate to the mid-scale equipment and that would be helpful if the need arose for a large scale gallery to be constructed to reproduce the characteristics of this facility in the future. This section therefore presents the following:

- Relationships between the air velocity measurements made by the portable anemometer, the array of anemometers and the differential pressure transducer in the duct
- Values for the power of the calibration fires (heat release rates) calculated from the quantity of gas consumed, the oxygen consumption measurements and the temperature rise values.
- Equations describing the temperature rise curves

5.4.1.1 Air flow measurements

From a graph plotted of the air flow measured by the portable anemometer (the nominal air velocity) and the mean of the array of nine fixed anemometers (the mean air velocity), the relationship between the two measurements was given by the equation:

\[
\text{Mean air velocity} = 0.9304 \times \text{nominal air velocity}
\]

As noted in 5.3.1.1 above, in the fourth calibration test the nominal air velocity was in conflict with the air velocity measured by the centre column of anemometers. For the power calculations it was important to have as accurate as possible a measure of the air velocity, thus the relationship between the velocity measured by the mean of the centre column and the nominal air velocity was determined. The relationship is given by:

\[
\text{Centre column mean} = 1.0489 \times \text{mean air velocity}
\]

The relationship between the duct differential pressure (duct dP) and the mean air velocity may be calculated by using the relationship:

\[
\text{Duct velocity} = 1.291 \times \bar{Q}(\text{duct dP})
\]

and by simply using the ratio of the area of the gallery and the area of the exhaust duct (0.636 m$^2$ for the duct diameter of 0.9 m). The relationship should theoretically be

\[
\bar{Q}(\text{duct dP}) = 4.87 \times \text{mean gallery air velocity}
\]

Hence

\[
\text{Duct velocity} = 1.291 \times 4.87 \times \text{mean gallery air velocity} = 6.29 \times \text{mean gallery air velocity}
\]
From the measurements made in the calibration tests the relationship was:

\[ \dot{Q}_{\text{duct \, dP}} = 5.04 \times \text{mean gallery air velocity} \]

and hence

Duct velocity = 1.291 \times 5.04 \times \text{mean gallery air velocity} = 6.51 \times \text{mean gallery air velocity}

### 5.4.1.2 Power calculations

The powers, or heat release rates, of the calibration fires were calculated using the following relationships:

**Propane consumption** \( P(P) \)

\[ P(P) = \text{Weight of gas burned} \times \text{Heat of combustion of Propane} \]

The heat of combustion of propane has been taken to be 46390 kJ/kg.

**Oxygen depletion** \( P(O) \)

The calculation of \( P(O) \) is based on work by Huggett [18], who showed that the heat of combustion could be taken to be 13 MJ/kg of oxygen consumed for many polymeric materials. Thus

\[ P(O) = 13 \times M \]

Where \( M \) is the mass of oxygen consumed per second. For a 1% depletion of oxygen in the exhaust gas

\[ M = V \times 0.01 \times \frac{r_p}{(1-0.199(F-1))} \]

Where

- \( V \) is the volumetric air flow
- \( r_p \) is the density of oxygen, here taken to be 1.3315 kg/m\(^3\), and
- \( F \) is the dilution factor, here taken to be 1.5

Thus

\[ P(O) = 13 \times V \times 0.1211 = 1.5743 \times V \]

**Temperature** \( P(T) \)

\[ P(T) = V \times r_a \times DT \times c \]

Where

- \( V \) is the volumetric air flow
- \( r_a \) is the density of air, here taken to be 1.205 kg/m\(^3\)
- \( DT \) is the temperature rise of the air, and
- \( c \) is the specific heat of air, here taken to be 1.012 \times 10^3 \text{ J/kg.deg C} \]
Table 11 below shows P(O) and P(T) values calculated using the nominal (P(O)n and P(T)n) and mean (P(O)m and P(T)m) gallery air velocities and the duct velocities (P(O)d and P(T)d). The table includes values of P(T)n and P(T)m at 15 minutes and 50 minutes for the test at a nominal air speed of 1.01 m/s for which only one burner was used. As noted above, in the tests with the second burner the gas flow was not regulated and appeared to have changed during the burn. For these tests the mean temperature over the burn period was taken for the calculation of P(T)n, P(T)m and P(T)d.

<table>
<thead>
<tr>
<th>Nom. air velocity (m/s)</th>
<th>Burner</th>
<th>P(P) (kW)</th>
<th>P(O)n (kW)</th>
<th>P(O)m (kW)</th>
<th>P(O)d (kW)</th>
<th>P(T)n (kW)</th>
<th>P(T)m (kW)</th>
<th>P(T)d (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>82.8</td>
<td>72.9</td>
<td>76.9</td>
<td>79.8</td>
<td>43.5</td>
<td>46.2</td>
<td>47.9</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>198.2</td>
<td>183.8</td>
<td>201.2</td>
<td>214.1</td>
<td>58.0</td>
<td>63.8</td>
<td>67.8</td>
</tr>
<tr>
<td>1.55</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>78.2</td>
<td>52.4</td>
<td>44.7</td>
<td>45.6</td>
<td>71.3</td>
<td>61.2</td>
<td>62.3</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>144.3</td>
<td>254.2</td>
<td>261.1</td>
<td>219.6</td>
<td>142.3</td>
<td>146.9</td>
<td>123.5</td>
</tr>
<tr>
<td>2.15</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>82.5</td>
<td>37.9</td>
<td>35.6</td>
<td>36.9</td>
<td>64.4</td>
<td>60.2</td>
<td>62.0</td>
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<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>113.4</td>
<td>147.8</td>
<td>140.9</td>
<td>143.2</td>
<td>101.5</td>
<td>95.4</td>
<td>98.8</td>
</tr>
<tr>
<td>1.01</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; (15min)</td>
<td>89.7</td>
<td>78.5</td>
<td>104.7</td>
<td>*</td>
<td>61.5</td>
<td>81.9</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; (50min)</td>
<td>89.7</td>
<td>78.5</td>
<td>104.7</td>
<td>*</td>
<td>55.2</td>
<td>73.5</td>
<td>*</td>
</tr>
</tbody>
</table>

* - duct pressure transducer not working

The following points arise from this exercise:

- For the powers calculated from oxygen depletion agreement with P(P) is good at the lowest air speed but is generally poor at the higher air speeds, probably because of the low response of the oxygen analyser.
- For the powers calculated from oxygen depletion the method of determining the air speed has little influence on the result.
- For the powers calculated from the grand mean temperature rise, agreement with P(P) at the lowest air speed is poor, probably because of the severe distortion of the air flow caused by the fire, i.e. the negative flow at the top of the gallery.
- At other air speeds P(T) values generally underestimate P(P), because the air temperature has not reached equilibrium, but are in better agreement than P(O) values.

5.4.1.3 Temperature rise curves

Vandervelde [19] developed a theoretical approach to evaluating quantitatively the heat released during reaction to fire tests. This involved determining the transfer function from two heat balance equations, one concerning the walls and the other concerning the air in the test box. The model was verified using data from tests on electric cables, and is claimed to provide a better estimate of heat release than the area under the temperature-time curve method. The analysis produces an equation of the form

\[ T(t)/K = A[1 - \exp(t/t_1)] + B[1 - \exp(t/t_2)] \]

Where

- \( T(t) \) is the temperature rise at time \( t \)
- \( K \) is the heat input

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A, B, \( t_1 \) and \( t_2 \) are constants, and 
\( t \) is the time.

The first part of the expression involving A and \( t_1 \) relate to the thermal response of the air in and flowing through the box, i.e. the short term component, while the second part involving B and \( t_2 \) relate to the thermal inertia of the walls i.e. the longer term component. At \( t = \tau \), \( T(\tau) \) is the temperature rise of the air at equilibrium, and

\[
T(\tau)/K = A + B
\]

This methodology has been applied to the calibration tests using the grand mean temperature – time curves for the first burner for the tests at 0.5, 1.55 and 2.15 m/s nominal air velocity and the whole 50 minute curve obtained at 1.01 m/s nominal velocity. Knowing the heat input rate \( (K=\dot{P}(P)) \) for each test enabled \( T(\tau) \) and hence \( (A + B) \) to be calculated, and curve fitting procedures were used to determine the four constants A, B, \( t_1 \) and \( t_2 \). Table 12 below shows the parameters obtained.

<table>
<thead>
<tr>
<th>Nominal air velocity (m/s)</th>
<th>Measured air velocity (m/s)</th>
<th>( T(\tau)/K ) (°C/Kw)</th>
<th>A (°C/kW)</th>
<th>B (°C/kW)</th>
<th>( t_1 ) (min)</th>
<th>( t_2 ) (min)</th>
<th>( R^2 ) (correlation coefficient)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.53</td>
<td>0.3867</td>
<td>0.1895</td>
<td>0.1973</td>
<td>1.10</td>
<td>85.6</td>
<td>0.9899</td>
</tr>
<tr>
<td>1.01</td>
<td>1.45</td>
<td>0.1414</td>
<td>0.0947</td>
<td>0.0467</td>
<td>0.81</td>
<td>15.3</td>
<td>0.9894</td>
</tr>
<tr>
<td>1.55</td>
<td>1.33</td>
<td>0.1541</td>
<td>0.1012</td>
<td>0.0529</td>
<td>1.08</td>
<td>26.4</td>
<td>0.9812</td>
</tr>
<tr>
<td>2.15</td>
<td>2.03</td>
<td>0.1010</td>
<td>0.0635</td>
<td>0.0374</td>
<td>0.752</td>
<td>35.8</td>
<td>0.9637</td>
</tr>
</tbody>
</table>

As mentioned above distortion of the air flow occurred in the test at a nominal 0.5 m/s air velocity resulting in a poor estimate of the power of the fire from the grand mean temperature rise. It is likely that this effect will result in poor estimates of the parameters in the curve fitting exercise. According to theory \( t_1 \) is inversely related to the air velocity, while \( t_2 \) is independent of air velocity and is related to the thermal capacity of the walls of the box.

### 5.4.2 Conveyor Belt Fire Tests

#### 5.4.2.1 Quantity of gas used

It has been noted above (Section 5.2.2.3) that the quantity of gas used in the conveyor belt tests was approximately 5.5 kg rather than 7.5 kg for the tests involving one burner. The possible effect of this reduced heat input needs to be examined to determine whether the validity of the test results is affected i.e. whether the test is a true test of resistance to propagation and whether the length of belt damaged is affected.

Section 3.3 of this report concerns the development of the High Energy Propane Burner test and in 3.3.1 it is noted that early work by the National Coal Board on a 26 mm thick steel cord belt produced the conclusions that the extent of damage depended on the total mass of gas consumed rather than on the consumption rate alone or the exposure time alone, and that 7.5 kg of propane was more than enough to completely destroy approximately one metre of belt near the burner. Section 3.3.3 explores the difference in behaviour of a belt in the 10 minute and 50 minute tests. Here it is seen that the extra time exposure can cause a major difference in the performance of a belt by ensuring that the belt over the burner becomes fully alight and burns away. It is also noted in 3.3.3 that the exposure time of 50 minutes is excessive for the example shown. Experience confirms that this is true of all but the heaviest of steel cord belts, since the majority...
of belts that pass the HE test burn away over the burner in substantially less than 50 minutes and self extinguish before the burner is turned off. Interpreting 3.3.1 in terms of 3.3.3 and of experience, the critical factor appears to be that sufficient heat is put into the belt over the burner for it to become fully alight and burn away. The burning belt thus becomes the principal source of heat input to the unburned belt in the critical area for resistance to propagation to be measured i.e. the region just beyond the influence of the burner. Since the belt was burned away over the burner in all of the tests made in this work it could be argued that 5.5 kg of gas is also more than sufficient and that the test is a true test of resistance to propagation.

However, it is important to examine also whether the amounts of damage caused to the belts in the present tests is comparable to that found in tests where 7.5 kg of gas were burned, as this could have a bearing on the setting of acceptance and rejection criteria in any new mid-scale test.

Two test results are available from the correlation tests referred to in Section 3.4, that give some comparative figures. The two belts were

¶ Belt X - 800 kN/m tensile strength, with 2 mm PVC covers and a mass of 16.54 kg/m
¶ Belt Y - 1750 kN/m tensile strength, with 2 mm PVC covers and a mass of 19.25 kg/m

For comparison Belt A has a tensile strength of 1750 kN/m, 1 mm PVC covers and a mass of 15.5 kg/m, thus being similar to one belt in mass and the other in strength. Table 13 below shows figures for these belts similar to those given in Table 10 and includes those from Table 10 for belt A at 1.5 m/s air speed.

<table>
<thead>
<tr>
<th>Test No</th>
<th>Length undamaged (mm)</th>
<th>Length consumed by weight (mm)</th>
<th>Length damaged (mm)</th>
<th>Length to flame front (mm)</th>
<th>Maximum average temperature rise (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>X1</td>
<td>2360</td>
<td>2260</td>
<td>876</td>
<td>1640</td>
<td>1740</td>
</tr>
<tr>
<td>X2</td>
<td>2370</td>
<td>2280</td>
<td>928</td>
<td>1630</td>
<td>1720</td>
</tr>
<tr>
<td>Y1</td>
<td>2690</td>
<td>2250</td>
<td>946</td>
<td>1310</td>
<td>1750</td>
</tr>
<tr>
<td>Y2</td>
<td>2650</td>
<td>2190</td>
<td>940</td>
<td>1350</td>
<td>1810</td>
</tr>
<tr>
<td>A1</td>
<td>2590</td>
<td>2530</td>
<td>765</td>
<td>1395</td>
<td>1455</td>
</tr>
<tr>
<td>A2</td>
<td>2860</td>
<td>3030</td>
<td>601</td>
<td>1160</td>
<td>990</td>
</tr>
</tbody>
</table>

It is not known, of course, whether these belts all possess the same degree of fire resistance since their compositions are unknown, but the figures provide some guidance on expected performance. For tests A1 and A2 the lengths undamaged appear to be rather higher than for Belt X and at the top end of the values for Belt Y i.e. the amount of damage is less than might be expected. This also applies to the lengths to flame front for these two test runs. However, for test A3 the situation is completely different and more damage than expected is seen. Whilst it is not uncommon for length undamaged to vary by 500 mm between repeat tests, the variability here is rather larger and useful information is obtained by examining the reasons for it.

The test piece used in test A3, was, as has already been mentioned in 5.2.2.3, initially used for a test at 0.5 m/s air velocity, which had to be aborted. During the few minutes of exposure to the burner at 0.5 m/s the usual deflection and shrinkage of the front of the test piece took place. When the test piece was used at 1.5 m/s nominal air velocity it was re-positioned with its front
edge at the front of the trestle, so that some of the shrinkage and deflection that normally occurred with this belt was eliminated. The extent of this repositioning was not recorded but is estimated to be approximately 100 mm. The values of length undamaged should therefore be increased by approximately 100 mm for test A3. However, this does not bring them into line with test pieces A1 and A2, and it may be that with some initial distortion and shrinkage being taken out of this test piece it sustained more damage and produced a higher maximum temperature rise. This suggests that fixing the front end of the belt to the trestle so that it could not distort and shrink from the burner would increase the severity of the test.

5.4.2.2 Effect of air velocity

Examination of the air velocities measured by the centre column of anemometers and inferred from the duct differential pressure shows

- In test A1 the actual velocity was 1.57 m/s
- In test A2 the velocity dropped almost linearly during the test from 1.5 m/s to 1.0 m/s just prior to the burner being turned off, giving a calculated mean of 1.3 m/s
- In test A3 the actual velocity was 1.71 m/s

Examination of the tests made at nominal air velocities of 1 and 2.1 m/s shows that the actual velocities as measured by the anemometers and inferred from the duct differential pressures were as follows:

- In test 7 the air velocity dropped almost linearly during the test from 2.39 m/s to 1.76 m/s just prior to the burner being turned off, giving a calculated mean of 2.08 m/s
- In test 8 the velocity was 1.36 m/s
- In test 10 the velocity was 2.24 m/s
- In test 11 the velocity was 1.0 m/s

Using these revised values for air velocity the effect of air velocity on propagation was examined by plotting the maximum length damaged against air velocity. As noted above the length damaged is derived from the length undamaged (as specified in British Coal Specification 158) by subtracting the latter from the test piece length and is independent of length. Figure 17 shows that there is a clear trend upwards in the length damaged as air velocity increases. The increase between 1.0 m/s and 2.24 m/s is approximately 700 mm.

It was noteworthy that for some of the tests involving larger fires than those considered above the air flow was changed by the fire.

The reasons for the decreases in air velocity seen in tests 5 and 7 is not known, neither is it known whether this effect has occurred in tests carried out in the past prior to the present work.

5.4.2.3 The Double Burner test

The test involving the use of the Double Burner provides some information on the effect of rate of heat input. In this test the gas supply to the top burner was uncontrolled and the rate of gas usage was over 50% greater than the 0.15 kg/min specified in BC 158, more than double the rate for the single burner tests reported here and over 75% greater than that specified in the Double Burner test method. Despite this high rate of heat input the maximum length damaged was 600 mm relative to the value from Figure 16 at 1.5 m/s, which is comparable to the increases seen between BC 158 tests and Double Burner tests made during the European correlation programme.
5.4.2.4 Flame front velocities

As noted above maximum flame front velocities were estimated for all of the tests where the belt thermocouple data allowed. Two values were obtained for each test i.e. from the “odd” and the “even” thermocouples and the mean of these two was taken as being representative. All of the values were determined by inspection of the graphical outputs rather than by computation. The velocities were estimated at an arbitrarily chosen temperature of 250°C.

The effect of air velocity on flame front velocity was examined but no clear trend emerged. However, as figure 18 shows, flame front velocity is almost functionally related to the estimated maximum rate of temperature rise in the plots of GM temperature against time. This is not altogether surprising, since if the temperature in the GM versus time plot represents the magnitude of the fire then its rate of change represents the rate of growth of the fire and hence the rate of flame spread. What is surprising is the correlation between the two measures.

Figure 17  Length damaged plotted against air velocity

Figure 18  Flame front velocity plotted against rate of GM temperature rise
It was noted during the determination of the flame front velocities that in tests where propagation was limited the temperature gradient became progressively steeper, reached a maximum when it was close to vertical (see figure 14), and then declined. In these tests the downwind temperatures remained low, whereas in those tests where propagation occurred the temperature gradients were always much flatter and downwind temperatures consequently higher.

5.5 COMMENTS

In a number of ways the tests in the large scale gallery fell short of what was originally planned because of the lack of time available and the difficulties of controlling such a large and ageing piece of equipment with precision. However, sufficient “redundancy” was built into the original programme to enable the objective of characterising the gallery to be met. This has been done with tests involving just the use of propane gas as the heat input and with “real” fires involving conveyor belts. The tests allowed an understanding to be developed of the way in which the gallery responded to a heat input and of the parameters that are important in the spread of fire down a conveyor belt. Useful data was obtained for the planning and execution of the next phase of the work involving the use of mid-scale tests to try to reproduce the performance of the large scale facility.

5.6 INTRODUCTION TO MID-SCALE GALLERY TESTS

As indicated in 5.1 above the conditions of test in the mid-scale gallery were varied as the test programme continued to seek to simulate the performance of belts in the large scale gallery. Thus the results of the tests in the initial phase of the programme of work in the mid-scale facility were used to set the test conditions in the next phase and so on. In this part of the report, therefore, the results of the tests at each phase of the programme i.e. each set of conditions, and the decision about the test conditions for the next phase, are presented together, before moving on to describe the testing carried out subsequently.

5.7 INITIAL CHARACTERISATION

5.7.1 Apparatus

The laboratory gallery used for this work was the United States Mines Safety and Health Administration (MSHA) gallery, which was referred to in the literature survey [17]. The gallery

Figure 19 General view of MSHA gallery
is 1676 mm long by 457 mm square in section and constructed from 25 mm thick refractory material. The square section is connected to a 300 mm diameter galvanised steel exhaust duct by a conical transition section (plenum). A smoke hood is positioned 50 mm above the entrance to the gallery. Air is drawn through the gallery by a fan positioned in the exhaust duct and the air speed through the gallery is controlled by dampers. A general view of the gallery is shown in figure 19.

The belt sample specified by MSHA is 1524 mm long by 228.6 mm wide, and is mounted on a trestle made from slotted angle iron. The sample is fastened to the trestle by a series of cotter pins inserted through it and into the trestle. The top of the trestle is 200 mm below the roof of the test chamber. The burner is a twelve jet methane gas burner, consuming 0.567 litres per second. The burner and test piece are arranged so that the sample is situated mid-way between the two rows of six jets so that the flames impinge on the end of the sample.

The arrangement of the burner, sample and trestle is shown in figure 20.

For these initial characterisation tests additional instrumentation was fitted to the MSHA gallery to allow the measurement of temperatures and oxygen depletions. Two measurements of the exhaust temperature were made. A 3 x 3 array of K-type thermocouples was fitted into the gallery beyond the trestle, as shown in figure 21, and a K-type thermocouple was inserted into
the exhaust duct downstream of the transition section.

An oxygen sampling probe was inserted into the duct alongside the thermocouple. It was not possible to fit additional anemometers into the gallery and so a single anemometer was used to

![Figure 22 Schematic of MSHA mid-scale gallery](image)

set the initial air flow. The positions of the duct thermocouple, oxygen probe and anemometer are shown in figure 22. For the tests involving belt samples fourteen K-type thermocouples were attached to the belt surface along the centre line of the belt sample using staples. For the first of these tests the first thermocouple was situated 150 mm behind the leading edge of the sample and the remainder at 100 mm intervals along the belt. For all other tests reported in this section the first thermocouple was placed at 200 mm behind the leading edge with the remainder at 100 mm intervals. The arrangement of thermocouples is shown in figure 23. The oxygen analyser and the data loggers used to collect the oxygen and temperature data were the same ones used in the tests in the large scale gallery.

5.7.2 Tests

Two types of test were made

- Tests with no belt sample present and only the burner ignited
- Tests with a sample of Belt A present

The tests without a belt sample present were made using both methane and propane as the fuel and at various flow rates and air speeds. For the tests with samples of belt present it was decided that the burner would be allowed to continue burning until either the section of belt on which the flames impinged had burned away and the belt had self extinguished, or the fire had propagated along the belt to the end of the sample. This decision was made in order to follow the logic used by British Coal in the propagation test in Specification 158, where the fifty-minute burn time was designed to ensure complete ignition of the sample. Tests were made using both methane and propane.
The decision to try propane as the fuel source was made because propane was the fuel used in the large scale test and because it is more readily available in the U.K. than is methane in appropriate capacities.

These initial tests were also intended to examine the usefulness of the measurements of temperature in the gallery and in the duct and of the oxygen depletions.

### 5.7.3 Results

The results of the first ten tests without a belt sample present are summarised in table 14 below. This table shows the rises in air temperature measured at the end of the “burner on” period both in the gallery (as the average of the nine readings, or grand mean, $\Delta T_{gm}$) and in the duct, ($\Delta T_{duct}$). The theoretical air temperature rise assuming equilibrium had been reached ($\Delta T_{th}$) is also shown, together with the powers of the fires calculated from the gas consumption rate ($P_{gas}$) the oxygen depletion measurements ($P_{Ox}$) and the temperature rise measurements ($P(T_{gm})$ and $P(T_{duct})$). Figure 24 shows a plot of $\Delta T_{gm}$ and $\Delta T_{duct}$ against time for a test under the standard MSHA conditions. In this figure the burner was lit at time = 0 minutes.

---

**Figure 23** Thermocouples attached to a conveyor belt sample
Table 14  Summary of results of first ten tests.

<table>
<thead>
<tr>
<th>Test No</th>
<th>Air Speed (m/s)</th>
<th>Gas</th>
<th>Gas rate (L/s)</th>
<th>Burner on time (min)</th>
<th>DT_{th}</th>
<th>DT_{gm}</th>
<th>DT_{duct}</th>
<th>P(gas)</th>
<th>P(Ox)</th>
<th>P(T_{gm})</th>
<th>P(T_{duct})</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1 M</td>
<td>0.567</td>
<td>15</td>
<td>79.8</td>
<td>80.2</td>
<td>72.9</td>
<td>20.3</td>
<td>19.3</td>
<td>20.4</td>
<td>18.6</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1 M</td>
<td>0.28</td>
<td>15</td>
<td>39.9</td>
<td>38.2</td>
<td>40.1</td>
<td>10.2</td>
<td>10.3</td>
<td>9.7</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1 M</td>
<td>0.71</td>
<td>20</td>
<td>99.7</td>
<td>107.9</td>
<td>94.6</td>
<td>25.4</td>
<td>25.1</td>
<td>27.5</td>
<td>24.1</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1 P</td>
<td>0.275</td>
<td>16</td>
<td>101.2</td>
<td>101.4</td>
<td>98.0</td>
<td>25.8</td>
<td>27.2</td>
<td>25.8</td>
<td>24.9</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.5 M</td>
<td>0.567</td>
<td>25</td>
<td>159.5</td>
<td>104.1</td>
<td>62.2</td>
<td>20.3</td>
<td>4.2</td>
<td>13.3</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1 M</td>
<td>0.567</td>
<td>25</td>
<td>79.8</td>
<td>89.8</td>
<td>73.8</td>
<td>20.3</td>
<td>21.1</td>
<td>22.9</td>
<td>18.8</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1.65 M</td>
<td>0.567</td>
<td>25</td>
<td>48.3</td>
<td>63.4</td>
<td>83.9</td>
<td>20.3</td>
<td>37.8</td>
<td>26.6</td>
<td>35.2</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0.5 M</td>
<td>0.567</td>
<td>25</td>
<td>159.5</td>
<td>103.2</td>
<td>60.9</td>
<td>20.3</td>
<td>8.8</td>
<td>13.1</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1 P</td>
<td>0.14</td>
<td>25</td>
<td>50.6</td>
<td>70.2</td>
<td>53.9</td>
<td>12.9</td>
<td>15.5</td>
<td>17.9</td>
<td>13.7</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1 P</td>
<td>0.21</td>
<td>25</td>
<td>75.9</td>
<td>104.8</td>
<td>74.8</td>
<td>19.3</td>
<td>23.1</td>
<td>26.7</td>
<td>19.0</td>
<td></td>
</tr>
</tbody>
</table>

An investigation was made at 1 m/s air velocity of the variation of temperature in the duct section where the temperature was measured to determine if the position chosen gave a proper representation of the exhaust temperature. The results are shown in figure 25, from which it can be seen that the position of the thermocouple has little effect on the measured temperature. At this air speed

![Figure 24](image-url)  
Figure 24  Plot of temperature rises with MSHA burner.
Three tests were made on Belt A. In two, the standard MSHA conditions were used (1.0 m/s air speed, 0.567 L/s gas flow, methane as the fuel, $P(gas) = 20.3$ kW), while in the other propane was used as the fuel at a consumption rate of 0.089 L/s ($P(gas) = 26.4$ kW), but otherwise the conditions were the same. In all three tests the belt caught fire rapidly over its whole upper length. In the tests with methane as the fuel the burner was turned off after eight and thirteen minutes respectively and with propane after five minutes. Figure 26 shows the temperature profile down the belt at various times in the test with propane fuel: the rapid progress of the fire down the belt is clear, and in marked contrast to the performance of the same belt in the large scale gallery (see figure 14).
A test on Belt B using propane gas (P(gas) = 26.4 kW), resulted in the burner being turned off after 7.5 minutes and the fire had to be extinguished after 14 minutes to avoid a dangerous situation.

The following points arise from these initial characterisation tests:

- The temperature rise measured in the first test (test 8) under the standard conditions specified by MSHA is very much higher than was measured in the large scale gallery.
- At an air speed of 1 m/s the power calculated from the oxygen depletion (P(Ox)) is close to that calculated from the gas consumption (P(gas)).
- At air speeds other than 1 m/s the agreement between P(gas) and P(Ox) is poor.
- The temperature rise measured in the duct is closer to the theoretical rise than that measured in the gallery, hence P(Tduct) is closer to P(gas) than is P(Tgm) and is a good measure of P(gas).
- The temperature of the exhaust air stabilises after approximately ten minutes.
- At 1 m/s air velocity the air temperature is uniform across the section of the duct.
- The instrumentation could give useful results at 1.0 m/s air speed.
- Tests with lower heat inputs should be made.

5.8 VARIATION OF TEST PARAMETERS AND ARRANGEMENTS

Following the initial characterisation tests, further runs were made with modified burner arrangements, all using propane as the fuel source. These included the use of the Franke burner at different gas flows and the MSHA burner with some combinations of the jets blanked off and with different gas flows. The Franke burner is a single jet burner similar in principle to a Bunsen burner, but having a ceramic screen, and is used as the heat input source for the DIN 22 118 fire test. It suffers from the disadvantage that debris falling from the belt can block or partially block the burner.

These further tests, made without belt present, gave a range of heat inputs from 2.6 to 9.1 kW, and on the basis of the temperature rises, a heat input of 5.0 kW was chosen for a test with Belt A. The burner used was the MSHA burner with all but the centre bottom four jets blanked off and the gas flow suitably reduced. In this test the belt pulled away from the burner and did not ignite during the 22 minutes for which the burner was lit.

Because of the failure of this test, the arrangement was changed slightly to include the two centre top jets as well as the centre bottom four, and the gas flow was increased to give a heat input of 9.1 kW. The belt initially ignited, burned away from the burner, appeared to go out, re-ignited and eventually self extinguished after 24 minutes. The length remaining undamaged was 835 mm.

This test arrangement was then used with a sample of Belt B, which burned away rapidly from the influence of the burner and self-extinguished, leaving 1210 mm undamaged.

Although clear progress had been made with this test arrangement, in bracketing an appropriate heat input and in that both types of belt had self extinguished, the fact that belt B performed better than Belt A meant that the test was not reproducing the situation in the large scale gallery where the reverse was true. This finding was significant and will be discussed later. Part of the problem was considered to be the geometrical relationship of the burner and the test piece, and it was decided that the burner should be re-designed to direct the heat input to the underside of
the belt sample (as in the large gallery). It was further decided that the existing slotted angle trestle was likely to be protecting a substantial area of the underside of the sample and was, in any case, positioning the sample too close to the gallery roof, causing high levels of heat to be fed back to the unburned part of the sample. A re-designed burner and trestle were produced and tested as described below.

5.9 TESTS WITH RE-DESIGNED BURNER AND TRESTLE

5.9.1 Description Of Burner And Trestle

The re-designed burner and trestle are described fully in Appendix A. Figure 27 shows the new test configuration in the gallery. Basically the burner consisted of two rows of three Type 373/1 Segas jets inclined at 45°, mounted on a suitable framework to position them beneath the belt sample. The trestle was 1500 mm long, 220 mm wide and 160 mm high, positioning the sample 300 mm below the roof of the gallery. It was made from 10 mm diameter mild steel rod and had suitable intermediate cross members to support the belt sample.

These new items were substituted for the original MSHA items, but otherwise the test facility remained as described above, except that the test piece size was standardised at 230 mm wide and 1500 mm long. For the initial test with the new equipment the trestle was placed 150 mm from the gallery entrance and the burner such that the first jet was 180 mm from the entrance.

5.9.2 Initial Tests

For the first test with the new equipment a sample of Belt A was wired down on to the trestle at the front edge only, otherwise the sample was unrestrained. The trestle was placed with its front edge 150 mm inside the gallery entrance and the burner 180 mm inside the entrance. With a heat
input of 9 kW for this test the belt lifted away from the burner by a vertical distance of about 150 mm after approximately two minutes and returned to lie flat on the trestle by about eighteen minutes. At 33 minutes visual observations showed that the belt was beginning to burn and the fire then progressed down the sample, increasing in intensity such that after 42 minutes it was extinguished for reasons of safety.

Examination of the duct temperature and oxygen depletion data showed that while the former increased gradually over the period between 3 and 39 minutes, the latter showed a modest rise from 3 to 28 minutes, followed by a flattening out to 39 minutes. At 39 minutes both measures increased very rapidly, indicating an extremely rapid increase in the intensity of the fire and the amount of belt burning.

It was considered that the reason for this rapid propagation was associated with the deflection of the belt away from the burner and the extended time when the heat from the burner was being directed less effectively towards the belt. A second test using Belt A was therefore made with additional restraint on the belt in the form of additional wiring at the centre and rear positions. The trestle was placed 160 mm inside the gallery, the burner was raised 25 mm from the floor of the gallery and repositioned to have its first jet in line with the front edge of the belt sample.

With the heat input again at 9 kW the belt initially lifted about 50 mm off the trestle in the region between the front and centre wiring, but returned to lie flat on the trestle after 5 minutes. After 10 minutes the belt was burning on both the upper and lower surfaces but gradually curled upwards out of the influence of the burner until after 24 minutes only small flickering flames could be seen on the belt. The belt then fell back towards the burner and at 31 minutes re-ignited under the influence of the burner. The test was terminated by turning off the burner at 50 minutes, by which time the belt had self extinguished, leaving a length undamaged on the top surface of 900 mm and on the bottom 850 mm. The length destroyed by weight was 285 mm, indicating that the belt had burned away only a short distance beyond the influence of the burner, which was estimated to be 250 mm.

Belt B was then tested under the same conditions, but with wiring at the front, rear and 300 mm from the front. Ten minutes into this test the belt had caught fire and had burned away approximately 450 mm from the front of the trestle. The burner was not influencing the belt directly at this stage although the belt was burning strongly. The fire increased in intensity before dying back, so that at 25 minutes the burner was turned off when the belt had almost extinguished. The lengths undamaged were 550 mm for the top and 540 mm for the bottom surface, with the length destroyed by weight being 770 mm, indicating substantial propagation beyond the burner.

Testing Belt C under the same conditions as Belt A resulted in a progressively increasing fire intensity such that at 20 minutes the burner had to be turned off and the fire extinguished for reasons of safety. The cover had burned away completely, but the carcase had not.

The revised test conditions therefore reproduced not only the rank order of the large scale gallery test, but also the manner in which the belts burned. Figure 28 shows the duct temperature rises for the three tests described above. The similarity with Figure 16 is striking.
5.9.3 Variation Of Parameters

Further testing was carried out to explore the effect of varying some of the test parameters. In tests made on Belt A the following were varied:

- the number of gas jets used,
- the gas flow rate,
- the height of the burner relative to the belt, and
- the restraint of the belt.

Number of gas jets

Reducing the number of jets to four, but keeping the flow rate the same produced almost identical results for all three belts as those quoted above for six jets.

Gas flow rate

Tests were made with both reduced and increased gas flows on samples of Belt A wired to the trestle at the front, rear and at intermediate positions. Over the range 5.2 kW to 17.2 kW the length undamaged reduced from 1070 mm to 650 mm on the top surface and from 960 mm to 820 mm on the bottom surface. These figures are derived from the results of single tests at the two extreme heat input rates, with three results at an intermediate value of 9 kW, and are therefore only indicative of the trend. It is noteworthy that an almost doubling of the heat input rate from 9 kW to 17.2 kW did not cause the belt to burn out but merely increased the length of damage to the top surface by 270 mm and the bottom surface by 100 mm.

Height of the burner

It has been reported above that when the burner was raised by 25 mm from the floor of the gallery and additional restraint was applied to the belt it did not burn out. A test with a heat input of 9 kW, with the burner on the floor of the gallery, but with the additional wiring decreased the length undamaged by about 100 mm on both top and bottom surfaces.
Restraint of the belt

A single test was carried out at 9 kW with the belt restrained only at the front and with the burner 25 mm above the floor of the gallery. The length undamaged increased by rather more than the 100 mm produced by lowering the burner.

5.9.4 Repeatability Tests

Following these exploratory tests, repeat tests were made on the three belt types at a heat input of 9 kW, with the burner raised 25 mm above the gallery floor and with the belt restrained by wiring down as described in Appendix A. The tests on Belts A and C gave similar results to those described above. However, whilst one test on Belt B gave similar results to those mentioned above, another test on Belt B was terminated by the test engineer using a fire extinguisher, because he considered that the fire was propagating rapidly and that a dangerous situation was imminent. Examination of the instrumentation outputs suggests that this termination may have been premature.

The results of the tests to examine the repeatability of belt performance are shown in table 15. The definitions of the various measures are the same as used in table 13.

Examination of the temperature profiles down the belts for samples of Belt A showed very similar features to those exhibited in the large scale gallery. In both galleries the furthest extent of the flame front coincided with a temperature of approximately 235 °C.

Flame front velocities were estimated for the tests shown in the above table, where the data allowed, in the same way as described in 5.4.2.4 above. Figure 29 shows the velocity values plotted against estimated maximum rates of temperature rise in the plots of duct temperature against time. Direct comparison with figure 18 is complicated by the differences in the temperature responses of the two galleries to unit heat input and the different specimen sizes. However, in absolute terms the velocities for Belts A and C are of a similar magnitude, while those for belt B are lower for the mid-scale gallery.

<table>
<thead>
<tr>
<th>Belt Type</th>
<th>Length undamaged (mm)</th>
<th>Length consumed by weight (mm)</th>
<th>Length damaged (mm)</th>
<th>Length to flame front (mm)</th>
<th>Maximum average temperature rise (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>A</td>
<td>900</td>
<td>850</td>
<td>285</td>
<td></td>
<td>600</td>
</tr>
<tr>
<td>A</td>
<td>860</td>
<td>930</td>
<td>230</td>
<td></td>
<td>640</td>
</tr>
<tr>
<td>A</td>
<td>920</td>
<td>880</td>
<td>350</td>
<td></td>
<td>580</td>
</tr>
<tr>
<td>B</td>
<td>550</td>
<td>540</td>
<td>770</td>
<td></td>
<td>950</td>
</tr>
<tr>
<td>B</td>
<td>400*</td>
<td>330</td>
<td>1050</td>
<td></td>
<td>1100</td>
</tr>
<tr>
<td>B</td>
<td>880**</td>
<td>740</td>
<td>715</td>
<td></td>
<td>620</td>
</tr>
<tr>
<td>C</td>
<td>0***</td>
<td>0***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>C</td>
<td>0***</td>
<td>0***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

* - test terminated by test engineer in interest of safety
** - approximately 100 mm of top cover remained intact in front of point to where carcase destroyed
*** - test terminated, covers destroyed to end of sample

Table 15 Results of repeat tests on Belts A, B and C
Overall the finding of this work on varying test parameters and on repeat runs with the new burner and trestle indicated that the test condition chosen for the repeat runs was probably an adequate simulation of the conditions in the large scale gallery for the performance of the test belts to be equivalent in the two circumstances. However the result of the test on Belt B that was terminated by the test engineer and the initial test with the new trestle and burner on Belt A indicate that with relatively minor variations the test conditions chosen could cause all three belts to burn out completely. In relative terms, therefore, the chosen test conditions in the mid-scale gallery were somewhat more severe than those in the large scale gallery.

5.10 CONFIRMATORY TESTS

A series of tests was made to examine the performance of other belt types in the new test arrangement. Details of the belts are given in table 16 below. The range of belts tested was chosen to:

- Examine the sensitivity of the test to changes in belt chemistry
- Examine the performance of a belt that was not fire resistant and would not have passed the High Energy test
- Examine the performance of a belt that would have passed the 10 minute propane burner test, but not the High Energy test
- Examine the performance of a number of belts that would encompass the complete range of belt types that are currently accepted for use in UK coal mines.
## Table 16  Details of additional belts tested

<table>
<thead>
<tr>
<th>Code</th>
<th>Construction</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Solid woven EbPe 875 N/mm PVC impregnated 1/1 rubber cover on 1/1 PVC</td>
<td>Same carcase as belt C, but with more fire resistant rubber cover.</td>
</tr>
<tr>
<td>E</td>
<td>315/3, EP 315 N/mm, 3/1.5 rubber covers, 7mm, 8 kg/m²</td>
<td>Non fire-resistant belt</td>
</tr>
<tr>
<td>F</td>
<td>EP 800 n/mm, 6.5/3 rubber covers, 15mm, 19.1 kg/m²</td>
<td>Met requirements of 10 minute test</td>
</tr>
<tr>
<td>G</td>
<td>EbPb, 1140 N/mm, PVC impregnated, 1/1 PVC covers, 9 mm, 12.3 kg/m²</td>
<td>Textile belt accepted for underground use, low end of strength range</td>
</tr>
<tr>
<td>H</td>
<td>EpPe 2100 N/mm, PVC impregnated, 2/2 rubber covers on 1/1 PVC, 18 mm, 23.8 kg/m²</td>
<td>Textile belt accepted for underground use, higher end of strength range</td>
</tr>
<tr>
<td>I</td>
<td>PpPe 2625 N/mm, PVC impregnated, 2/2 rubber covers on 1/1 PVC 19.5 mm, 24.5 kg/m²</td>
<td>Textile belt accepted for underground use, high end of strength range</td>
</tr>
<tr>
<td>J</td>
<td>ST2200, approx 8/8 rubber covers, 18 mm, 33.4 kg/m²</td>
<td>Steel cord belt accepted for underground use, low end of strength range</td>
</tr>
<tr>
<td>K</td>
<td>ST7000, approx. 7/7 rubber covers, 28.5 mm 63.1 kg/m²</td>
<td>Steel cord belt accepted for underground use, highest of strength range</td>
</tr>
<tr>
<td>L</td>
<td>Cable belt (virtually all cover) 17 mm 22.9 kg/m²</td>
<td>Belt accepted for use in cable belt installations underground</td>
</tr>
</tbody>
</table>

The results of these tests are shown in table 17 below.

The following points arise from the results of these tests:

- The test is able to distinguish between different qualities of cover on the same carcase.
- The repeatability of the test, as shown by the tests on Belt D, is good.
- The belt that was not fire-resistant (Belt E) caught fire after only 4 minutes exposure and had to be extinguished.
- The belt that had met the 10 minute test requirements started to burn rapidly after 14 to 15 minutes, having survived 10 minutes of exposure to the burner.
- All of the belts that were tested to represent the complete ranges of those currently accepted for underground use using the High Energy test, performed well in the new test, none recording a length damaged of more than 650 mm.
Table 17  Results of tests on additional belts

<table>
<thead>
<tr>
<th>Belt</th>
<th>Length undamaged (mm)</th>
<th>Length destroyed by weight (mm)</th>
<th>Maximum temperature rise (°C)</th>
<th>Length damaged (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper</td>
<td>Lower</td>
<td></td>
<td>Upper</td>
</tr>
<tr>
<td>D</td>
<td>1080</td>
<td>1060</td>
<td>335</td>
<td>71.0</td>
</tr>
<tr>
<td>D</td>
<td>1140</td>
<td>1120</td>
<td>340</td>
<td>71.0</td>
</tr>
<tr>
<td>D</td>
<td>1110</td>
<td>1070</td>
<td>285</td>
<td>67.0</td>
</tr>
<tr>
<td>D</td>
<td>1070</td>
<td>1030</td>
<td>299</td>
<td>66.0</td>
</tr>
<tr>
<td>E</td>
<td>Burner turned off after 4 min., fire extinguisher used at 4.5 min.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Burner turned off after 4 min., fire extinguisher used at 5.25 min.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Satisfactory at 10 min., took off after 15 min., burner off at 16.25 min., fire extinguisher at 18 min.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Satisfactory at 10 min., took off after 14 min., burner off at 15.5 min., fire extinguisher at 17 min.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>1055</td>
<td>1060</td>
<td>335</td>
<td>58.9</td>
</tr>
<tr>
<td>G</td>
<td>870</td>
<td>890</td>
<td>428</td>
<td>81</td>
</tr>
<tr>
<td>H</td>
<td>1100</td>
<td>1010</td>
<td>230</td>
<td>69</td>
</tr>
<tr>
<td>H</td>
<td>1110</td>
<td>1070</td>
<td>236</td>
<td>66.8</td>
</tr>
<tr>
<td>H</td>
<td>1040</td>
<td>990</td>
<td>300</td>
<td>80.0</td>
</tr>
<tr>
<td>I</td>
<td>860</td>
<td>980</td>
<td>316</td>
<td>79.8</td>
</tr>
<tr>
<td>I</td>
<td>960</td>
<td>1080</td>
<td>295</td>
<td>73.5</td>
</tr>
<tr>
<td>J</td>
<td>1070</td>
<td>970</td>
<td>301</td>
<td>70.6</td>
</tr>
<tr>
<td>J</td>
<td>1050</td>
<td>950</td>
<td>303</td>
<td>70.2</td>
</tr>
<tr>
<td>K</td>
<td>1220</td>
<td>935</td>
<td>131</td>
<td>72.5</td>
</tr>
<tr>
<td>K</td>
<td>1230</td>
<td>970</td>
<td>N/a</td>
<td>N/a</td>
</tr>
<tr>
<td>L</td>
<td>1120*</td>
<td>1000*</td>
<td>245</td>
<td>60.2</td>
</tr>
<tr>
<td>L</td>
<td>1140*</td>
<td>1030*</td>
<td>240</td>
<td>54.6</td>
</tr>
</tbody>
</table>

* - sample was 1110 mm long, lengths calculated for 1500 mm standard sample.

From these results it was therefore concluded that the new test could be used to simulate performance of belts in the large scale gallery.

5.11 ACCEPTANCE REQUIREMENTS

The acceptance requirements in BC 158 are set out in table 2 contained in Section 3.1. For ease of reference they are repeated here. They are:

either
a) 2250 mm left undamaged, or
b) Maximum average temperature rise not exceeding 90 °C, length consumed by weight not exceeding 2000 mm and 250 mm undamaged, or
c) Maximum average temperature rise of 80 °C, length consumed by weight not exceeding 2250 mm and 250 mm undamaged

In the absence of a mathematical model relating the two galleries, a pragmatic approach was taken to setting proposed acceptance criteria for the new test.

It is possible to match a) by expressing the damage in terms of the amount of propagation allowable beyond the length over which the burner flames impinge directly on the belt. In BC 158 this length is about 1000 mm and in the new test it is about 250 mm. To achieve a pass by
criterion a) a belt could have a length damaged of 1750 mm (4000 mm test piece minus 2250 mm undamaged = 1750 mm damaged). Subtracting from this the distance of 1000 mm over which the burner flame impinge gives a distance of 750 mm of allowable damage beyond burner. The equivalent acceptable length of damage in the new test is then 1000 mm (250 mm burner impingement plus 750 mm beyond), and an undamaged length therefore of 500 mm (1500mm sample length minus 1000 mm).

The maximum average temperature rise is the maximum value of the difference between the average exhaust gas temperature and the incoming air temperature taken over a period of one minute. It is a measure of the maximum allowable heat release rate. In BC 158, if in any one minute period the average difference between the exhaust temperature and ambient is greater than 90 or 80 °C for criteria b) and c) respectively, the belt fails.

To relate the temperature rise allowable in BC 158 with that allowable in the new test account must be taken of the differences in air flow and fuel consumed and the effect of increased temperatures on propagation. The volumetric air flow in the large gallery is much higher than that in the mid-scale gallery, but the latter uses less fuel than the large gallery, both in terms of the quantity of propane gas used and the amount of belt that is burned. Carrying out the calculations to allow for these differences reveals that a one degree temperature rise in the large gallery is approximately equivalent to a three degree rise in the smaller gallery. Using a ratio of 3 as a conversion produces temperature rises in the mid-scale gallery of 270 and 240 °C as being equivalent to 90 and 80 °C respectively in the large gallery. However, the limited experience available with Belts B and C suggests that temperatures above 170 °C result in complete destruction of the belt sample, Since account has to be taken of the likely increase in propagation caused by high temperatures in the restricted environment of the mid-scale gallery, a maximum allowable temperature rise of 170 °C, or somewhat below it, would be more practical. This limit represents a significant tightening of the maximum heat release rate requirement.

On the same basis as length undamaged i.e. from the end of the influence of the burner, for criterion b) the length consumed (by weight) could fall within the length of the MSHA test piece, but for c) this length comes at the end of the sample, and is therefore impracticable. A value for length consumed by weight for the new test would be 1250 mm for criterion b).

Because of the length of the test pieces in the two tests it is not possible to find an equivalent length undamaged to the figure of 250 mm in criteria b) and c) in the BC 158 requirements. However it was considered that there should be some length of belt remaining undamaged and a figure of 50 mm was suggested for criterion b); criterion c) would have no equivalent.

Following inspection of the results and consultation with both the HSE Project Manager and J H Fenner, it was considered that criterion a) could be tightened to 600 mm. Similarly it was considered that the temperature rise figure for criterion b) should be set at 140 °C, so that Belt B would be a marginal failure. The following agreed acceptance criteria are proposed:-

Either

a) >600 mm of belt undamaged with no maximum temperature requirement, or
b) >50 mm left undamaged, maximum temperature rise in the duct of 140°C and a maximum length consumed by weight of 1250 mm.

Two runs on each belt type if covers are of equal thickness and 3 runs if they are not, with the third run being a repeat of the worse of the first two.

These requirements can, of course, be revised in the light of further experience with the new test method.
6 DISCUSSION

The three principal objectives of this research programme were to:

- Characterise the large scale gallery
- Identify, characterise and develop small scale tests
- Seek to understand the importance of changes in test conditions

6.1 CHARACTERISATION OF LARGE GALLERY

A full characterisation of the large gallery has been provided in terms of:

a) air velocity distributions across the gallery cross section at three air speeds,
b) the relationship between the mean air velocity and the differential pressure in the exhaust duct
c) the response of the gallery to known heat inputs, and
d) the performance of three different types of conveyor belt.

From the additional instrumentation used it was evident during this work that there were problems with the control of the large gallery. It is not known to what extent these problems were inherent in the gallery design and to what extent they were a result of the age of the installation.

A by-product of the characterisation work was the finding that the extent of damage to a belt increases with air speed in this gallery and with this set-up geometry.

6.2 SMALL SCALE TESTS

The MSHA mid-scale gallery was identified as a potentially suitable vehicle for the development of a laboratory-scale test. The instrumentation used allowed the relative severities of the original MSHA and large scale tests to be assessed. The modifications that were made progressively to the MSHA set up resulted in a test that appears to correlate well with the large scale test. However, the lack of extensive sets of data or previous results on a wide range of belts prevented a more detailed and truly quantitative correlation being established. The heat input rate of 9 kW that has been established for the proposed new test is approximately twice that used in the large scale test in terms of heat input per unit air flow through the galleries and almost 50% higher in terms of nominal heat input per unit area of belt on which the flames impinge. In this sense, therefore, the new test is more severe than the large scale test. A test with a 5 kW heat input, which was much closer to the large gallery in terms of heat input per unit air flow, was not successful in igniting the belt sample. However, in this test the belt was not as closely restrained as in subsequent tests and this may have affected the result. Time constraints prevented the further exploration of the effect of heat input rate and the distance of the burner below the sample, which also affects the actual heat input to the belt. However, from the success of the correlation achieved in the test programme it appears that belt performance is not very sensitive to heat input rate as long as the surface temperatures down the sample remain similar to those in the large scale test.

The tests carried out at air velocities other than 1.0 m/s in the MSHA gallery gave poor correlation of the theoretical and measured temperatures and powers, suggesting that the setting of the damper in the exhaust duct that controls the air flow in the particular apparatus used here was influencing the uniformity of the temperature and oxygen distributions across the duct cross section. This effect, together with time constraints, prevented tests being made at air velocities other than 1.0 m/s.
6.3 CHANGES IN TEST CONDITIONS

Whilst the brevity of the test programme has limited the extent to which test conditions could be varied, there was sufficient variation in the test programme carried out for a number of useful observations to be made.

The first of these observations has been recorded above, i.e. increasing air velocity in the large scale gallery caused increasing damage to the belt sample for the same heat input and set up geometry.

Changing the burner geometry by using the double burner was not conclusive in this work because of the limited data available. However, previous tests carried out as part of the CEC correlation tests [5] showed that almost doubling the rate of heat input by using the double burner caused an increase in the amount of damage of about 600 mm for the lightest belts, but this decreased progressively as belt weight increased until for the heaviest belts there was no increase. This confirms that the capacity of the belt to absorb heat is an important factor in resistance to propagation. It also indicates that the extent of propagation is not very sensitive to the rate of heat input in the large gallery.

In the mid-scale gallery, results of tests with varying heat input rates are only available on Belt A. Here again almost doubling the heat input rate caused a relatively small increase in propagation. However, changes to the burner geometry and the degree of restraint of the belt sample appear to be more significant.

Tests with the original MSHA burner at a heat input rate of 9 kW resulted in a greater amount of propagation for Belt A than Belt B, whereas the later burner geometry at the same heat input rate and the large scale tests reversed this order. With the MSHA burner Belt B burned away rapidly from the end, so that at any one time only a small amount of belt was burning. This is evidenced by the maximum duct temperature rise of only 53 °C compared with over 150 °C for the revised burner geometry. With the MSHA burner geometry Belt B would have easily met the criteria now proposed for acceptance. It appears from this limited amount of information that the performance of belts is much more sensitive to the way in which the heat attacks the belt than the magnitude of the heat input.

Further evidence of this is provided by the differences in propagation for Belt A when the new burner was on the floor of the gallery and when it was raised by 25 mm from the floor. The former of these produced complete burnout because a greater amount of the burner heat was heating the air and gallery walls which in turn heated the downstream parts of the belt sample. When the belt ignited, therefore, the downstream parts of the sample were much closer to the ignition temperature than when the burner was raised 25 mm and more of the heat was being absorbed by the sample itself. The need to impose adequate restraint on the sample so that the proportion of the burner heat directed at the sample remains constant further emphasises this aspect.

The fact that it is possible to get the “wrong” answer in terms of belt performance by changing burner geometry is important in terms of relating performance in laboratory tests to performance in service situations. In this context the geometry in which the burner is situated beneath the belt is a better simulation of a typical belt fire underground due to a failed idler than is the original MSHA burner geometry.
7 CONCLUSIONS

1 The project has satisfactorily achieved the first of the objectives by characterising the large scale gallery in terms of:

(a) air velocity distributions across the gallery cross section at three air speeds,
(b) the relationship between the mean air velocity and the differential pressure in the exhaust duct
(c) the response of the gallery to known heat inputs, and
(d) the performance of three different types of conveyor belt.

2 The project has identified, characterised and developed a small scale test based on the MSHA mid scale gallery that adequately simulates the performance of the large scale gallery.

3 A new test method had been provided, together with drawings of the apparatus needed and proposed acceptance levels in Appendix A of this report.

4 The work done has provided important insights into the factors that affect fire propagation on conveyor belts, the most important of which appears to be that changes to the burner/belt geometry relationship can cause significant changes in propagation performance because of changes in the heat distributions.

5 The report provides a history of the development of fire propagation tests used for the acceptance of conveyor belts for use in underground mines and a review of recent work carried out that has been relevant to the project and that underpins the development of the new test.
8 ACKNOWLEDGEMENTS

The authors wish to express their appreciation for the assistance provided to them by International Mining Consultants Ltd., who carried out the large-scale gallery tests and of J H Fenner & Co Ltd., who carried out the mid-scale gallery tests as a contribution in kind to this project.

The assistance of the Health and Safety Executive’s Project Manager is also gratefully acknowledged.
9 REFERENCES


5. Yardley, E. D., Commission of the European Community Directorate General V ‘Harmonisation Of The Fire Safety Test Methods On Conveyor Belting For Use Underground In The CEC’, Report Co-ordinating the Findings of ECSC Research Projects 7262/03/313, 7262/03/314, 7262/03/315 and 7262/03/316


20. BS 4250 ‘Liquefied Petroleum Gas – Part 1 Specification For Commercial Butane And Propane’
APPENDIX A

PROPOSED MID-SCALE FIRE PROPAGATION TEST FOR CONVEYOR BELTING

A1 INTRODUCTION

This proposed test is intended to replace the High Energy Propane Burner test described in British Standard 3289 and the technically equivalent British Coal Specifications 158 which apply to textile carcase conveyor belts and in British Coal Specification 730 which relates to steel cord belts. It has been developed because the closure of the fire test gallery formerly owned by British Coal left the U.K. without a test facility in which the resistance to fire propagation of conveyor belts as measured by the High Energy Propane Burner test could be assessed. Tests using this proposed method have demonstrated that belts that would pass the High Energy test would also pass this new test.

Because the test procedure involves the measurement of the exhaust temperature and the acceptance requirements include a maximum temperature rise figure, a procedure is given in the Annex to this Appendix for calibrating the exhaust temperature to correlate with the performance of the equipment on which this test method was developed.

A2 SCOPE

This test method provides a means of assessing the resistance of conveyor belting intended for use in underground mines to the propagation of fire.

A3 PRINCIPLE

A sample of conveyor belt is subjected to a source of ignition provided by a gas burner. The extent of damage to the belt sample and the rise in the temperature of the exhaust air are measured.

A4 EQUIPMENT

A4.1 Test Gallery

The test gallery is shown in Figures A1 and A2. A test chamber made from 25 mm thick refractory material, having an opening measuring 460 mm x 460 mm and 1676 mm long is connected to a 300 mm diameter exhaust duct by a conical transition section (plenum). Air is drawn through the gallery by means of a fan situated in the exhaust duct. The speed of the air is controlled by dampers. A suitable exhaust hood is placed over the test chamber to extract smoke and fumes that may escape from the front of the chamber during a test.

A4.2 Support Frame

A support frame, shown in figure A3, is used to carry the belt sample. The frame is 1500 mm long, 220 mm wide and 160 mm high. It has suitable lugs by which the belt sample may be wired down to the frame.

A4.3 Burner

The gas burner is shown in figure A4, and consists of six Type 373/1 Segas jets mounted in two rows of three inclined at 45 degrees inwards and positioned on a suitable frame to place them beneath the test sample.
A4.4 Gas Supply

Propane gas to BS 4250 Part 1 [20] is supplied to the burner via a flowmeter capable of measuring a flow rate of 345.5 litres per hour.

A4.5 Air Velocity Measurement

The velocity of the air is measured by means of an anemometer positioned on the centreline of the test chamber at a height of 310 mm above the floor and 285 mm from the front.

A4.6 Temperature Measurement

A K-type thermocouple, connected to a recording device capable of recording the temperature not less than six times per minute, is positioned in the exhaust duct as shown in figure A1.

A4.7 Timer

A suitable timer capable of measuring to one second.

A4.8 Scales

Scales suitable for weighing the belt samples and the gas bottle.

A5 PREPARATION

A5.1 Test Pieces

For belts with top and bottom covers of equal thickness cut two test pieces measuring 1500 mm long by 230 mm wide in a longitudinal direction from the conveyor belt to be tested. Avoid taking the test pieces from within 50 mm of the edge of the belt. For belts with covers that are not of equal thickness cut three test pieces.

Allow the test pieces to lie flat for 24 hours prior to testing.

Weigh the test pieces.

Lay a test piece on the support frame and secure it to the frame using 25 gauge wire as follows:

Make four 8 mm diameter holes through the belt 50 mm in from each side of the belt and 50 mm from the front and rear of the test piece. Pass the wire through the holes and secure the belt to the frame.

Make two 8 mm diameter holes through the test piece 20 mm in from the sides and 330 mm from the front edge. Pass the wire through the holes and secure the belt to the frame.

Pass two loops of wire over the test piece at positions 100 mm and 250 mm from the front and secure the test piece tightly down to the frame.

A5.2 Installation Of The Test Piece And Burner

Place the support frame in the test chamber centrally with the front edge of the test piece 160 mm from the front of the test chamber.
Install the burner centrally beneath the support frame such that the first two jets are in line with the front edge of the test piece.

**A6 PROCEDURE**

Weigh the gas bottle prior to the test.

Set the air velocity at $1.0 \times 0.05$ m/s using the anemometer positioned as described in A4.5 above.

Record the temperature of the exhaust air for 2 to 5 minutes to give a measure of the ambient air temperature.

Set the gas flow to approximately 350 litres per hour and light the burner. Start the timer. Adjust the gas flow to $345 \times 5$ litres per hour.

After 50 minutes turn off the gas to the burner and allow the test piece and support frame to cool.

Weigh the test piece after removal from the support frame and the removal of loose char.

Weigh the gas bottle at the end of the test.

Terminate the test if the extent of the fire appears to be a danger to persons or equipment.

**A7 MEASUREMENT OF DAMAGE**

Measure from the rear end of the test piece to the furthest extent of the fire damage. Count any cracks, blemishes or blisters not originally present as damage. Record this length as the minimum length undamaged.

**A8 TEMPERATURE RISE**

From the temperature measurements taken during the test calculate the maximum average temperature rise over ambient in any one minute period during the test. Record this value as the maximum average temperature rise.

**A9 NUMBER OF TESTS**

For belts with covers of equal thickness carry out two tests.

For belts with covers of unequal thickness carry out three tests, one with each cover downwards and the third as a repeat of the worse of the first two.

**A10 CALCULATION**

Calculate the length destroyed by weight in millimetres using the relationship

$$\text{Length destroyed by weight} = \frac{\text{Weight before test} - \text{weight after test}}{\text{Weight before test}} \times 1500 \text{ mm}$$

**A11 REPORT**

Report the following:
The date of test.
The complete identification of the belt.
The minimum length undamaged for each test piece.
The maximum average temperature rise for each test piece.
The length destroyed by weight for each test piece.
The weight of gas consumed.
Any deviation from the test procedure.

**A12 ACCEPTANCE REQUIREMENTS**

The belt shall have met the requirements of this test if for each of the test pieces either

a) the minimum length undamaged for each test piece is not less than 600 mm, or
b) the minimum length undamaged is not less than 50 mm, the maximum average temperature rise is not greater than 140 degrees Centigrade and the maximum length consumed by weight is not greater than 1250 mm.

Where any of the tests is terminated prematurely for reasons of safety to persons or equipment the belt shall be deemed to have failed to meet the requirements of this test.
Figure A1 Overall view of test gallery

1. EXHAUST DUCT Dia.300
2. EXHAUST DUCT Dia.150
3. EXHAUST HOOD
4. TEST CHAMBER 25mm THICK REFRACTORY MATERIAL
5. BURNER DRG.No.2336-2
6. BELT RACK DRG.No.2336-1
7. BELT SAMPLE 230mmx1500mm
8. DEBRIS TRAY 1.5mm TH. STAINLESS STEEL
9. PLENUM

THERMOCOUPLE AND OXYGEN ANALYSER

VIEW ON -A-

THERMOCOUPLE AND OXYGEN ANALYSER

ANEMOMETER POSITION

EXHAUST HOOD NOT SHOWN

FRONT FACE

EXHAUST HOOD

500mm APPROX. SCALE

180

160

175

175

510

TITLE

LABORATORY-SCALE FIRE TUNNEL
Figure A2 Details of test gallery

ITEM 9 PLenum 1off 304 STAINLESS STEEL 1.5mm TH.

ITEM 3 EXHAUST HOOD 1off 304 STAINLESS STEEL 1.5mm TH.

ITEM 4 TEST CHAMBER 1off

SELF TAPPING SCREW
150 TYP. 9 TIMES

SELF TAPPING SCREW
80x25Lg.--44off

25x25x3 RSA

25mm TH. REFACTORY MATERIAL

CUT FLOOR AND RSA AS SHOWN
TO FIT PLenum ITEM 9

ITEM 8 DEBRIS TRAY 1off

SEE DRG.2336 FOR BELT SUPPORT AND GAS BURNER

TITLE
LABORATORY-SCALE FIRE TUNNEL
DETAILS
Figure A3  Test piece support frame
ANNEX TO APPENDIX A

EXHAUST TEMPERATURE CALIBRATION.

When operated at the standard gas flow of 345 °5 litres per hour without a belt test piece present, the exhaust gas temperature measured in the duct over the final minute of the 50 minute test should record a rise over ambient of 50 °5 degrees Centigrade. When plotted against time the temperature rise above ambient should follow the form shown in figure AA1.

Figure AA1   Exhaust duct calibration graph
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