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THE DESIGN, CONSTRUCTION AND EVALUATION OF
A MID SCALE COMBUSTION TEST APPARATUS

By

RICHARD JOSEPH HEATH, MSc., GPRI., LRIC.,

A Doctoral Thesis Submitted In Partial Fulfilment
Of The Requirement For The Award Of Doctor Of
Philosophy Of The Loughborough University Of Technology,
November, 1976.

Supervisor: D.E. MARSHALL, PhD.,
Department of Polymer Technology

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ACKNOWLEDGMENTS

I would like to take this opportunity to thank Shell Research (formerly Egham, now Amsterdam) for funding this research topic, and the Science Research Council for allowing me a grant to live frugally over the last three years. In addition, I would like to thank my supervisors, Doctors David Marshall and Marianne Gilbert for their time and ideas in this project, along with Peter Ramsey and his technical staff (especially Barry and Malcolm for taking my ideas from paper and producing working electronic systems and mechanical units from them). Also British Aircraft Corporation (Weybridge) for use of their fire test facilities and British Rail (Derby) for carrying out the critical oxygen index tests.

Finally, I would like to thank Mrs. M. Heath for her usual typing skills.

---------

This thesis is dedicated with great affection to my parents, who knew I could do it even though I had serious doubts.
ABSTRACT

A medium scale fire test rig was designed, constructed and tested. Early experiments showed it to have potential in establishing fire data for furnishing composites, which paralleled values produced from full scale fire tests. The apparatus had facilities to continuously monitor temperatures, smoke emission and carbon monoxide, along with analysis of other toxic gases and general observations of the fire.

Later tests showed direct comparisons with certain full scale tests were impossible due to the inability to parallel exact fire conditions and geometries of sample. However, this mid scale test had relevance in establishing the manner in which ignition and the early stages of propagation proceeded in a fire, and showed this to be a function of the fabric covering in the furnishing composites used.

In addition some typical small scale fire tests and semi-micro thermal analyses have been carried out. Also included in the thesis are diagrams and scale drawings of the test facility, along with typical graphs of fire parameters derived from tests.
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ABBREVIATIONS

A
AMINCO NBS
ASTM
c
C/A
CAA
C₆H₅OH
CO
CO₂
COI
D
Dₘ
Dₛ
Dₛ₁
DTA
FAA
FR
FRS
GRP
HCHO
HCl
HCN
HDPE
HF
HR
IBT
ICUP
k
L
LDPE
M
MAC
MDI
NFR
NH₃
NO
NO₂
NOₓ
NOD
O
O₂
PE
PF
PMMA
PP
ppm
PPVC
PS
PTFE
PU
PVC
RAPRA
RH
Rm
S
SO₂

Initial Surface Area of AMINCO NBS Smoke Test Sample.
American Standard & Test Methods.
Smoke Concentration.
Cotton Acrylic Fabric.
Civil Aviation Authority.
Phenol.
Carbon Monoxide.
Carbon Dioxide.
Critical Oxygen Index.
Optical Density.
Mass Specific Optical Density.
Specific Optical Density.
Specific Optical Density at 1 Minute.
Differential Thermal Analysis.
Federal Aviation Authority.
Fire retarded Polyurethane Foam.
Fire Research Station.
Glass Reinforced Polyester.
Formaldehyde.
Hydrogen Chloride.
Hydrogen Cyanide.
High Density Polyethylene.
Hydrogen Fluoride.
High Resilience Polyurethane.
Ignition Burn Time.
Inter-Company Urethane Panel.
Constant Dependent on Type of Smoke Particle.
Natural Rubber Latex Foam.
Light Transmission Path Length in AMINCO NBS Smoke Chamber.
Low Density Polyethylene.
Mass of Sample Lost in AMINCO NBS Smoke Test.
Maximum Allowable Concentration of Toxic Gas.
4,4'-Diphenyl Diisocyanate methane.
Non Fire Retarded Polyurethane Foam.
Ammonia.
Nitrous Oxide.
Nitrogen Dioxide.
Nitrogen Oxides.
Neutral Optical Density.
Obscuration.
Oxygen.
Polyethylene.
Phenol Formaldehyde.
Polymethyl Methacrylate.
Polypropylene.
Parts Per Million.
Plasticised Polyvinyl Chloride.
Polystyrene.
Polytetra-Fluoro-Ethylene.
Polyurethane (Leathercloth).
Polyvinyl Chloride (Leathercloth).
Rubbers & Plastics Research Association.
Rubberised Hair.
Maximum Rate of Smoke Increase in AMINCO NBS Test.
Sulphur Dioxide.
ABBREVIATIONS (Contd).

T Transmittance.
TC1 Thermocouple Placed Centrally 10 cm from Backwall, at 90 cm from the Floor (Preliminary Set-up).
TC3 Thermocouple Placed Centrally 10 cm from Backwall, at 60 cm from the Floor (Preliminary Set-up).
TC5 Thermocouple Placed Centrally 10 cm from Backwall, at 30 cm from the Floor (Preliminary Set-up).
TC11 Thermocouple Placed Centrally 90 cm from the Floor (Preliminary Set-up).
TC13 Thermocouple Placed Centrally 60 cm from the Floor (Preliminary Set-up).
TC15 Flexible Thermocouple.
TC1 Thermocouple Placed Centrally 30 cm from the Floor (Present Set-up).
TC2 Thermocouple Placed Centrally 60 cm from the Floor (Present Set-up).
TC3 Thermocouple Placed Centrally 90 cm from the Floor (Present Set-up).
TC4 Thermocouple Placed Centrally 10 cm from Backwall, at 30 cm from the Floor (Present Set-up).
TC5 Thermocouple Placed Centrally 10 cm from Backwall, at 60 cm from the Floor (Present Set-up).
TC6 Thermocouple Placed Centrally 10 cm from Backwall, at 90 cm from the Floor (Present Set-up).
TDI 2, 4 and 2, 6 Tolyene Diisocyanate.
TGA Thermogravimetric Analysis.
Tm Melting Point Temperature.
UF Urea Formaldehyde.
UPVC Unplasticised Polyvinyl Chloride.
V Volume.
V2 Volume.
W Woollen Fabric.
W Width of Sample in AMINCO NBS Test.
WF Woollen Flock.
W/R Wool Rayon Fabric.
Q Density.
CHAPTER 1: INTRODUCTION
1.1. A Brief Historical Review

1.1.1. The Nature of Fire

The human race has employed fire in its many forms for perhaps a million years. This use has included heating, cooking, the thermal treatment of materials, warfare, etc., and in its many guises fire has proved both friend and enemy.

The fire phenomena has intrigued man for at least its period of use. Initially, it was the obtaining and subsequent control of fire, and more recently its abstract study (with mankind desiring the knowledge of one of the mysteries of life). The Greek philosophers sought after the nature of fire, putting it alongside earth, air and water as one of the basic elements. This ideology was to last until the middle of the 18th Century. Theophrastus (373 to 287 B.C.) was one of the earliest scientific observers and experimenters of fire; Farrington (1) describes some of these findings. This Greek was somewhat unusual in that he carried out his own experiments, a field of study well beneath the dignity and class of most ancient philosophers. So, as with much scientific study of this period, its experimental skill did not develop and thought became fixed for the next millenium.

In this dark age, when scientific ignorance or the word of the Greek philosophers was absolute, the alchemists thought fire was part of the answer to the "philosopher's stone" and the production of gold from base metals. Gradually the mystery and the magic gave way to primitive chemical and physical ideas, and history had reached the mid Renaissance.

Francis Bacon in the 17th Century (2) conjectured heat could be a form of motion in microscopic particles of matter, while general
scientific opinion was confused, thinking fire was perhaps a material substance. The study of chemical reactions started to reveal some of the truth, but unfortunately became entangled into the Phlogiston Theory. In 1731 Stahl elaborated an earlier idea that the "element of fire" was supposed to be released during the combustion of a body; this element or "oily earth" was renamed terra pingus or Phlogiston. It was defined as a fatty solid impossible to isolate, which went out in a flame to combine with the air. By 1750 this theory was the established convention and for another 30 years it was to hold sway.

Then in 1783 Laviosier, in conducting very carefully controlled heated chemical reactions, introduced the concept of a "caloric" or weightless species present during combustion. Since then the piecing together of basic chemistry and physics of combustion reactions has progressed steadily, particularly with advancement of thermodynamics and kinetics, (eg. the nature of the candle flame was revealed by Michael Faraday in the 1840's).

The discovery and use of polymers during the present century has called for research into their properties and in particular their reaction to fire conditions. Due to the nature of the material compounded from a polymer, the fire study of the material has become a complex thing. A discussion of the phenomena of fire on polymers with particular reference to present day research is found in Chapters 2 and 3.

1.1.2. The Nature of Fire Hazard

Over its period of use fire has been a potential hazard to man and his environment. It was discovered early that fire had to be specially
contained, and without preventive measures would escape to do damage. The great fires of historic record include those used to deliberately raze Troy after the legendary 10 years siege, Rome during Nero's reign and the Great Fire of London in 1666. In the latter instance, legislation based on common sense followed, to ensure city planning and building construction would minimise fire spread and so loss of life and property. In this century requirements have become sophisticated, demanding only certain types of construction and materials be used in public and private buildings. Nevertheless at the present, laws only cover a fraction of materials used in building construction and furnishings.

Taylor (3) has suggested the basis of the following table, which shows the chronology of introduced legislation and resulting containment of fire:

**TABLE 1.**

<table>
<thead>
<tr>
<th>Approximate Period</th>
<th>Potential Fire Spread Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 1700 AD</td>
<td>Whole Cities or Towns</td>
</tr>
<tr>
<td>1700 to 1900</td>
<td>Blocks of Dwellings</td>
</tr>
<tr>
<td>1900 onwards</td>
<td>Single Buildings</td>
</tr>
<tr>
<td>1970 onwards</td>
<td>Room Where Fire was Initiated</td>
</tr>
<tr>
<td>Estimated 2000 onwards</td>
<td>Piece of Furniture Where Fire was Initiated</td>
</tr>
</tbody>
</table>

(The dates in this table have been estimated from the trends in fire research, and from estimates of when fire-resistance materials will be generally available in the market-place).

In the West, because of public concern and strict laws, fires in high rise buildings, such as that which occurred in San Paulo, Brazil (4), will be extreme rarities and hopefully limited to the Hollywood epic.
With present day technology and resources, fire danger can be limited to the ignition source (e.g. dropped lighted match or cigarette or live coal). Materials are available, if expensive, which are thermally stable and resistant to spread of fire, and could be used in potentially dangerous conditions. When and if this happy state is reached, the final commitment in fire prevention is education, i.e. the gentle but firm and regular reminders of the DOs and DONTs connected with fire safety. The implications of this education are sociological and outside the area of this work, but are discussed by Scott (5).

1.2 Present Day Fire Problem

1.2.1. Polymers and Fire: The Problem

At the present time unsuspected hazards contribute to fire danger which legislation can only deal with after an incident. This points to deficiencies with the legislation and human failing, i.e. in the case of public buildings, failure to comply with fire-drill and escape procedure. After an ensuing fire, materials or design are often criticised in non-constructive debate in the press (see Chapter 1.2.2.) when often these are not to blame for endangering life, but the fact that the fire-drill or escape procedure had not been properly observed.

However, the vehement attack on polymers in the press, though not leading to any immediate solutions, may be partially understood in terms of the annual increase in lives lost (5) as shown in Table 2, especially when the use of plastics and rubbers has also greatly increased.
TABLE 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Fires with Fatalities in UK</th>
<th>Number of Fatalities in All Fires Attended in UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>449</td>
<td>529</td>
</tr>
<tr>
<td>1961</td>
<td>492</td>
<td>572</td>
</tr>
<tr>
<td>1962</td>
<td>595</td>
<td>667</td>
</tr>
<tr>
<td>1963</td>
<td>721</td>
<td>818</td>
</tr>
<tr>
<td>1964</td>
<td>611</td>
<td>681</td>
</tr>
<tr>
<td>1965</td>
<td>594</td>
<td>703</td>
</tr>
<tr>
<td>1966</td>
<td>648</td>
<td>780</td>
</tr>
<tr>
<td>1967</td>
<td>652</td>
<td>779</td>
</tr>
<tr>
<td>1968</td>
<td>670</td>
<td>865</td>
</tr>
<tr>
<td>1969</td>
<td>716</td>
<td>861</td>
</tr>
</tbody>
</table>

The following table shows the total loss of property by fires:

TABLE 3

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Property Loss £m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>100</td>
</tr>
<tr>
<td>1969</td>
<td>120.4</td>
</tr>
<tr>
<td>1970</td>
<td>110.9</td>
</tr>
<tr>
<td>1971</td>
<td>128.7</td>
</tr>
<tr>
<td>1972</td>
<td>141.2</td>
</tr>
<tr>
<td>1973</td>
<td>176</td>
</tr>
</tbody>
</table>

Data for other parts of the world is also available in a variety of publications (eg. 6, 7).

Polymers are now often replacing the traditional and essentially non-flammable materials (eg. those based on metal or glass) in everyday use and may possibly aggravate a potential fire hazard. Often there are no checks to assess the fire properties of the materials but slowly the problem is now being recognised, and society may have to balance the contribution of polymers to the quality of life against possible fire hazard.
1.2.2. Polymers and Fire: The Public Debate

Since 1970, an increasing number of articles have appeared in both the popular national and technical press, detailing concern over the flammability of polymers. The greatest concern of the press is when the public is involved in fires or possible fire hazardous conditions. The Summerland fire on the Isle of Man generated a number of articles (8) on the safety from fires of public buildings. Detailed stories with very harrowing photographs of burning multi-storey dwellings have, for example, received full coverage in the colour supplements (4).

Although a few articles in the daily press have been written to evoke an emotional response in their readers (eg. 9), the majority have been of a common sense or factual based nature. These range from details of the material and life loss (10, 11) in the financial press, to a variety of technical information in the trade press.

This type of press treatment has provoked lobbying of government to introduce legislation banning the use of certain polymers. Polyurethane foams used in domestic furniture have been the most vehemently attacked in parliament, being accused of "spontaneously igniting", or even "spontaneously exploding into flame". (12). Polyurethane manufacturers have erred on the slow side in coming to their own defence, rather awaiting the findings of their own private research before replying (13).

Because of the massive turnover in polyurethane and the present use of polyurethanes in domestic furniture, it is impossible to stop the use of the foam while awaiting conclusions. Grants have been made to the Rubber and Plastics Research Association and the Fire Research Station to examine fires in domestic environments.
The polymeric forms receiving most adverse publicity are those used in the home. These include polystyrene ceiling tiles, electrical insulation, along with the plastics and rubbers used in furniture, including television cabinets, carpets, drapes, bedding and particularly soft furnishings. A considerable amount of polyurethane (mainly flexible with some rigid) is used in the two latter items. It has been calculated that in the 20 years preceding 1973, $10^8$ cubic feet of polyurethane had been manufactured and used in the United Kingdom alone. Other seat fillers (eg. cotton and woollen flock, rubberised hair and latex foam) have been declining over this period, to well under 10 per cent of the market. Therefore in a domestic fire, polyurethane is statistically more likely to be involved than any other material.

Polyurethane now has a virtual monopoly of the seating fillers, in the field of transportation (ie. passenger cars, railway carriages and passenger aircraft). They meet the basic requirements of comfort, long life, physical properties and being better than any other materials in fire testing.

In the unlikely circumstances of fire occurring, polyurethane receives the notoriety when, in fact, the other possible seating candidates have been eliminated at the research or development stage for being greater hazards than polyurethanes (18).

The chemical and physical reactions of polyurethanes to fire environments are discussed in Chapter 3.
CHAPTER 2: THE ASPECTS OF FIRE
2.1. Fire and Polymers

Polymers are having an ever increasing impact on everyday life being cheaper and easier to process than most other materials.

This is shown for a single application in Table 4.

TABLE 4: Consumption of Polymers in Furniture in United Kingdom (19)

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Consumption in 1968 (x 10^3 tonnes)</th>
<th>Predicted Consumption in 1980 (x 10^3 tonnes)</th>
<th>Average Annual Growth (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>6</td>
<td>36</td>
<td>16</td>
</tr>
<tr>
<td>LDPE</td>
<td>&lt;1</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>HDPE</td>
<td>&lt;1</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>PS</td>
<td>1</td>
<td>24</td>
<td>29</td>
</tr>
<tr>
<td>PP</td>
<td>3</td>
<td>39</td>
<td>22</td>
</tr>
<tr>
<td>UF</td>
<td>20</td>
<td>33</td>
<td>4</td>
</tr>
<tr>
<td>PF</td>
<td>4</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>UP</td>
<td>&lt;1</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>PU (flexible)</td>
<td>14</td>
<td>39</td>
<td>8</td>
</tr>
<tr>
<td>PU (rigid)</td>
<td>&lt;1</td>
<td>3</td>
<td>12</td>
</tr>
</tbody>
</table>

The majority of the popularly used polymers are flammable, and in fire situation very often contribute to fire spread. Few legislative bodies demand minimum flammability requirements for materials, until a number of catastrophes strike. The exceptions include the world's main aircraft licensing body, the Federal Aviation Authority of the United States, who also demand maximum levels of smoke (and soon toxic gas) released from materials used inside the fuselage of passenger aircraft. The aircraft industry along with others are now evaluating high temperature resistant polymers for possible end-use. The price of these materials restricts their use to the "luxury market" of aerospace, and as such prohibits their use in the domestic environment. Surprisingly few furniture manufacturers show concern in even setting fire standards let alone looking at expensive fire-resistant materials, and most await legislation before acting (20).
Fire regulations are limited in most countries to standards for clothing, furnishings in publicly used buildings (e.g. hospitals) and non-metallics used in public transport. In many applications polymers only have to meet the following requirements:

(i) physical properties to the equivalent of the material they are replacing or up to the job they are expected to do
(ii) cost comparison
(iii) good appearance

To this list may be added comfort in the case of furnishings.

In looking at and setting fire standards, properties that may effect safety are:

(i) ease of ignition
(ii) speed of fire spread
(iii) resistance to penetration by fire
(iv) production of smoke
(v) production of toxic gases and oxygen depletion.

2.2. Mode of Ignition and Fire Spread in Polymers

Ignition is the phenomena of fire being initiated in a material by an external agency, and if the fire takes hold fire spread results. Throughout, "fire" will refer to the act of a material burning, releasing heat, gases and smoke, and this burning is observable in two major modes:

(i) flaming: heat, gases and some smoke released mainly in a visible flame from a combustion reaction (e.g. air fed reaction)
(ii) smoldering: heat, gases and smoke released mainly by the material burning by self-heating, without showing any flame. This is normally by a pyrolysis reaction (e.g. limited air fed reaction).
Hilado (21) has suggested a polymer passes through a number of steps before reaching a "burning well" stage (ie. supporting and supplying the fire from its own material). These steps are expanded upon as follows:

(i) the polymer may be heated by external sources (ie. a flame or by radiant, convectional or conductional heat) and later, once fire has established itself in the body of material, from the fire within itself. A heat flux falling over an area of the polymer can produce this pro-ignition sequence:
   (a) heating above ambient temperature,
   (b) softening, when an unsupported plastic may droop into the heat source,
   (c) melting at Tm, producing hot droplets (which could be burning) which can fall away from the main burn area.

Depending on the polymer, softening and melting may occur before or after the next step:

(ii) the polymer reaches a temperature at which thermal degradation occurs. Here the least thermally stable chemical bonds rupture, often by a complex free radical mechanism (22)

(iii) the polymer now reaches the pyrolysis stage. It is now converted into smaller molecules, eg. usually monomer from additional polymers (for example, styrene from polystyrene), parent molecules from condensation polymers, (for example, polyol and isocyanate from polyurethanes). They may remain in the condensed phase to be later volatilised by additional heating or become gaseous species. Flammable molecules will contribute fuel, which will burn in the presence of a flame, or collect to form a potentially explosive mix.

With the additional heating and rise in temperature, smaller molecules are produced. Molecules will also react among
FIG 1: TYPICAL PYROLYSIS PATTERN IN A BURNING POLYMER.
themselves and with any atmospheric oxygen (eg. especially in combustion reactions), giving rise to complex organic and oxidised molecules, (eg. carbon monoxide, carbon dioxide and nitrogen oxides). Heat of combustion or pyrolysis will be released during all of these reactions.

(iv) Pyrolysis in most polymers involves the formation of two zones:
   (a) the pyrolysis zone which moves into the solid, away from the surface as material in being vapourised,
   (b) a char zone between the surface of the unburnt polymer and the pyrolysis zone, usually consisting of a porous solid residue (See Figure 1).

(v) A polymer can undergo primary pyrolysis in the pyrolysis zone and secondary pyrolysis in the char zone if the gaseous products formed in the primary pyrolysis are further reacted.

(vi) If the secondary pyrolysis occurs as a flaming reaction, combustion occurs. In the case of flame spread, heat from the flame front increases the temperature of the solid polymer in advance of the flame, so that the polymer undergoes rapid degradation, pyrolysis and gas release. This heat is delivered by radiation and conduction, and to cause spread will have to accelerate the vapourisation rate and exothermic reaction rate such that the temperature is raised to the ignition point just as the flame front reaches that location. At faster rates of vapourisation and reaction, flashover may happen (ie. the phenomena of flame leaping across apparently unaffected material). The principle exothermic reaction often takes place in the gas phase between combustibles diffusing away from the solid char, whilst burning has been described as a "continuous diffusive gas phase ignition".

12
FIG 2: SCHEMATIC REPRESENTATION OF POLYMER'S REACTION TO FIRE.
This set of mechanisms give a generalised picture of the ignition and post ignition behaviour of a polymer. Pyrolysis reactions and decomposition products, and so succeeding oxidative reactions and combustion products vary with:

(a) material type (whether singularly or in composition)
(b) temperature
(c) heat flux
(d) endotherms
(e) amount and characteristics of any solid char
(f) oxygen supply.

Figure 2 shows some of the inter-relationships of the above scheme. Van Krevelan (23) has stated decomposition of non-volatile organic materials proceeds in two stages:

(i) primary decomposition between 350 to 550°C, with softening and often formation of a tar
(ii) secondary decomposition above 550°C, when the primary char formed in the first stage is carbonised to a final char residue with the formation of a hydrogen rich gas. This stage terminates between 800 to 1000°C.

Some indication of ignition temperatures and burning rates can be made by thermodynamic studies (e.g. differential thermal analysis) and bond energy determinations (24) of the structure of a polymer (assuming it is not too complex). There is a tendency for polymers with high heats of combustion to have relatively low ignition temperatures and hence high flammabilities (25). High bond dissociation energies (i.e. the energy required to break structural chemical bonds) tend to increase molecular stability (25). In addition, a polymer with a low cohesive energy tends to be of a low melting point and as such is an easily volatilised molecular species, cohesive energy is defined as the total
energy required to remove a molecule from a liquid or a solid. It relates to the secondary bond forces in molecular aggregates in the non-gaseous phase.

Polar groups, high molecular weight and hydrogen bonding increase cohesive energy. Tables 5 and 6 give some examples of these energies:

**TABLE 5: Heat of Combustion and Bond-Dissociation Energies of Some Molecular Species (25)**

<table>
<thead>
<tr>
<th>Bond Type</th>
<th>Heat of Combustion (Kcal/mole)</th>
<th>Bond Dissociation Energy (Kcal/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;C=C&lt;</td>
<td>203.2</td>
<td>—</td>
</tr>
<tr>
<td>&gt;C=O&lt;</td>
<td>121.8</td>
<td>100 to 125</td>
</tr>
<tr>
<td>&gt;C-C&lt;</td>
<td>52.9</td>
<td>59 to 70</td>
</tr>
<tr>
<td>&gt;C-H</td>
<td>52.7</td>
<td>87 to 94</td>
</tr>
<tr>
<td>&gt;C-O-</td>
<td>15.0</td>
<td>70 to 75</td>
</tr>
<tr>
<td>&gt;C=0</td>
<td>0</td>
<td>142 to 166</td>
</tr>
<tr>
<td>&gt;C-N&lt;</td>
<td>—</td>
<td>49 to 60</td>
</tr>
<tr>
<td>&gt;N-H</td>
<td>—</td>
<td>84 to 97</td>
</tr>
<tr>
<td>&gt;C-Br</td>
<td>—</td>
<td>54</td>
</tr>
<tr>
<td>&gt;C-Cl</td>
<td>—</td>
<td>67</td>
</tr>
</tbody>
</table>

**TABLE 6: Molar Cohesive Energies of Some Molecular Species with Reference to Polyurethanes (25)**

<table>
<thead>
<tr>
<th>Group</th>
<th>Cohesive Energy (Kcal/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocarbon (-CH₂-)</td>
<td>0.68</td>
</tr>
<tr>
<td>Ether (-O-)</td>
<td>1.00</td>
</tr>
<tr>
<td>Ester (-COO-)</td>
<td>2.90</td>
</tr>
<tr>
<td>Aromatic (C₆H₄-)</td>
<td>3.90</td>
</tr>
<tr>
<td>Amide (-CONH-)</td>
<td>8.50</td>
</tr>
<tr>
<td>Urethane (-OCONH-)</td>
<td>8.74</td>
</tr>
</tbody>
</table>
As can be seen from the tables, heat of combustion and bond dissociation energies are far more significant than the cohesive energies.

Thermal stability of a polymer usually relates to high fire resistance. Under ideal circumstances a polymer subjected to a short exposure of heat should not:

(a) physically deform or lose physical properties
(b) melt or drastically soften (i.e. distort under its own weight, and in doing so possibly come into closer contact with the heat source).
(c) thermally degrade.

Eirich et al (26) have stated the basic requirements for high polymer stability, namely:

(a) high melting or softening temperature
(b) high resistance to spontaneous pyrolysis
(c) chemical inertness.

High temperature resistant polymers have these properties and consist at a molecular level of inflexible recurring ring systems (e.g. 5 or 6 carbon atoms in aliphatic rings, or aromatics) with the minimum of aliphatic straight chain present. These are often called "ladder polymers". Maximum chain stiffening and stability occur where the rings are fused together (e.g. "Nomex", an aromatic polyamide, has a combination of pronounced chain rigidity with lateral hydrogen bonding). However these polymers often have the following problems associated with them:

(a) intractability, i.e. once synthesised, cannot be processed satisfactorily
(b) expensive
(c) limiting mechanical properties
However certain of these polymers have been processed into fibres which in turn have been made up into high temperature resistant fabrics.

A fire will continue to burn naturally until the following occur:

(i) material completely burnt away
(ii) oxygen supply is drastically reduced; even so smoldering can occur at low levels of the gas
(iii) char builds up so as to impede further pyrolysis
(iv) gases form to smother fire, by preventing ingress of oxygen to the fire site
(v) it is doused by outside means.

2.3 Fire Resistance and Its Measurement

Flammability is a vague term covering a number of possible reactions of a material to a fire situation, and more specifically to combustion. As such, it may refer to any of several fire properties, each of which may be determined by a different test. Recent articles have appeared suggesting definitions of flammability can and should be tightened up (27, 28). The rigorous control of definitions can be seen as very necessary especially when tests have prescribed a material as "self-extinguishing" or "non-combustible", when in real fire situations the material may burn readily.

There is also a need to standardise a lot of so-called flammability test methods, of which there are at least 100 in the United Kingdom alone. Variations of test set up, procedure and assessment of burn characteristics occur from industry to industry, often depending on the final requirements of a company for a material. Even in the popularly used standards we can get BS 4422 defining flammability as
"the capacity of a material to burn", ASTM E 176-66 defining it slightly more precisely as the "ease of ignition and rapid flaming conditions". However, one standard test method will not fulfil all criteria of flammability assessment. Just consider the difference in mode of burn for carpets and curtains, as BS 476 Parts 3 to 9 verify. The differences between countries' tests, however, are becoming smaller as a result of International conferences and committees, and let us hope at least universal agreement on correlation and conforming related methods will not take too long.

Kelly et al (29) and Burgess et al (25) reviewed flammability tests, the latter specifically related to cellular materials. Often these tests fail to reproduce the effects of geometry, composite construction and modes of heating that exist in real fires. It has been suggested that any tests, other than full scale tests, are "small scale tests" and these flammability tests fall under this heading. They are mostly conveniently carried out in laboratory fumehoods at low expense of manpower and materials. There are very few "full scale fire tests" because of the high expenditure of materials, staff and test area used; those particularly relating to furnished articles are more fully described below in Chapter 5.

Kelly et al (29) suggest that in assessing flammability, ignitability or rate of flame spread, there had often been confusion between the meaning of the three terms when, in fact, all were quite different properties of a material although flammability could be a function of the other two. The same authors indicated flammability is orientation dependent (ie. the position of the flame in relation to the specimen). Flammable materials burn more readily when ignited at their lowest point than when ignited at the highest point, since
heat rises to come into contact with more material in the former, and much combustion heat is lost to the air above in the latter. The burn can be further complicated by the heated polymer melting. The hot melt either remains in situ (ignition at the top of the sample) or drips taking heat from the combustion site (ignition at base), the latter instance giving heat and possibly flame an opportunity to reach objects otherwise away from the initial burn area. The so-called "self-extinguishing" conditions arise if enough heat can be removed from the fire site so that pyrolysis or combustion reactions cease.

Most flammability tests are initially at room temperature (an exception being the heated critical oxygen index test), preventing a relative measurement of flammability to be made at high temperatures. This has relevance when considering an aircraft fire where heat outside the aircraft may cause spontaneous combustion or flashover to materials inside.

2.3.1. Small Scale Flammability Tests

Small scale flammability tests are becoming severe with strict test procedures and standards for assessing a pass or fail state for a material. Kelly et al (29) have discussed methods of establishing specific fire parameters including:

(i) heat of combustion (ISO/R 1716 - 1971 (E)), ie. the amount of heat released by the complete combustion of a unit mass of material

(ii) ignitability (BS 4422 : 2 : 1971) ie. ability of a material to be ignited by a standard flame

(iii) surface spread of flame (BS 476 : 17 : 1971) ie. the rate of flame spread over the surface of a material.
Taylor (30) has recently reviewed a number of British Standards relating to fire testing. The bulk of tests assess "flammability" which may be indicated by any number of resultant fire parameters. The majority of tests are cheap and quickly operated bench tests, using the minimum of equipment and test specimens, the most complex piece of apparatus being a stop watch. Normally the fire is initiated by a flaming source. The best tests define the following fixed setting-up requirements:

(a) standard shaped specimen (of variable thickness)
(b) standard ignition source
(c) ambient air temperature and pressure
(d) preconditioning of sample
(e) free supply of air in initially still air conditions
(f) rigid geometry of sample.

If a burner is used as the standard ignition source, the additional requirements are laid down:

(a) standard flammable gas composition
(b) standard gas pressure and flow rate to give a standard flame geometry and temperature
(c) standard flame height
(d) fixed exposure time of the material to the flame
(e) standard distance of the flame tip to the sample.

These resulting parameters may be then measured as indicators to the degree of flammability:

(a) burn time of specimen
(b) char dimensions (e.g., length, width or height)
(c) any burning drops
(d) observation of the flame characteristics
(e) burn through time.
Thus arbitrary values can be assigned to the materials, showing whether it is self extinguishing, non-burning, self supporting or slow burning, or else an estimate of rate of flame spread can be made. On the whole the so-called flammability tests measure inter-related parameters together and in terms of quality control, there is no real need to distinguish between them.

Three typical small scale quality control tests are used to assess the flammability characteristics of materials in this research. These are described in the experimental section of this thesis (Chapter 9). They include:

(a) vertical strip test
(b) horizontal strip test
(c) inclined plane strip test (or alcohol cup test).

Hall (31) has described the major United States flammability tests and problems arising from their use.

2.3.2. Critical Oxygen Index Test

Over the last ten years the critical oxygen index (COI) test has introduced some sophistication to the measurement of flammability of a material. The method has been praised in most quarters, but recently it has been suggested it does not fulfil all that is desired of a universal flammability test. Its versatility is discussed by Day (32).

The method (ASTM D 2863) essentially determines the minimum concentration of oxygen in a slowly changing mixture of oxygen and nitrogen which will cause a thin strip of material to support combustion in a candle-like manner (i.e. downward burn. The normal atmospheric concentration of oxygen (i.e. 20.95% vol) is the demarcation line between the self-supporting and self-extinguishing
states; and also gives some idea of ignitability of a material (see Table 7).

TABLE 7: Some Critical Oxygen Index Values for Polymers

<table>
<thead>
<tr>
<th>C.O.I. (% vol. O₂)</th>
<th>Description of Burn Characteristics</th>
<th>Typical Polymers</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;28</td>
<td>Self extinguishing</td>
<td>&quot;Nomex&quot;, PTFE, UPVC</td>
</tr>
<tr>
<td>26 - 28</td>
<td>Will not burn horizontally but up vertically</td>
<td>Some silicone, rubbers, polycarbonate</td>
</tr>
<tr>
<td>22 - 25</td>
<td>Will not burn horizontally but burn in all vertical directions</td>
<td>PP, some PPVC, PE, wool, nylon</td>
</tr>
<tr>
<td>&lt;21</td>
<td>Will burn in all directions (ie. self-supporting)</td>
<td>PU, GRP, PAMA, PS, cellulose</td>
</tr>
</tbody>
</table>

It should be noted that varying orientation produces changes in critical oxygen index for a material (see Table 8).

TABLE 8: Comparison of Mode of Orientation in Burning

<table>
<thead>
<tr>
<th>Material</th>
<th>Mode of Orientation</th>
<th>Critical Oxygen Index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scots Pine (12-15% moisture content)</td>
<td>Vertical - burning upwards</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Vertical - burning downwards</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Horizontal - with air flow</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Horizontal - against air flow</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Vertical - burning upwards</td>
<td>20</td>
</tr>
<tr>
<td>Expand polystyrene</td>
<td>Vertical - burning downwards</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Horizontal - with air flow</td>
<td>21.5</td>
</tr>
<tr>
<td></td>
<td>Horizontal - against air flow</td>
<td>22</td>
</tr>
</tbody>
</table>

The critical oxygen index test has been correlated with other flammability tests (33, 34) and it has been suggested it would be dangerous to use it as a replacement for other fire tests, but should be used in conjunction with them. One Japanese standard (J.I.S. D1201) calls for three screening tests to be used to evaluate materials, ie. critical oxygen index test, vertical flammability test and smoke.
obscuration. It has been reported that the critical oxygen index test does not correlate with the BS 476 fire spread test (33).

The basic critical oxygen index test may be varied to study the effect of raising the initial atmospheric temperature on the fire resistance of a material (35). The temperature oxygen index is defined as the temperature at which the oxygen index of a material becomes 20.9%. It is thought of immense value in obtaining a numerical assessment of relative flammabilities of materials, avoiding the ambiguous terms of self-extinguishing and low flammability. It has been used to explain why certain polymers (e.g. plasticised polyvinyl chloride) have high critical oxygen indices, but burn in fire situations.

Another variation is used in the aircraft industry to assess a vertical strip flammability test in various oxygen concentrations (i.e. parallelling oxygen rich conditions sometimes found in aircraft).

2.3.3. Recent Innovations

Small scale flammability test apparatus are reported in literature and at conferences of great innovation, including mode of operation and measurement of resulting fire parameters. Several of these were built to establish the validity of mathematical models of fires and revealed at the International Symposium on Fire Safety, Edinburgh in 1975.

At the larger end of the small scale test apparatus are those which measure a large number of different fire properties (36, 37).

2.4. Smoke Evolution of Burning Polymers and Its Measurement

Smoke is decomposition product from a fire that remains in suspension.
in the air for some time. It consists of a mixture of solid particles (primarily soot from incomplete combustion), vapour (eg. water, monomer) pyrolysis and combustion gases. Berman (38) has stated that the fire products from a polymer involved in a fire depend on the following:

(a) chemical composition of polymer
(b) its physical state (eg. foamed or solid, pigmented, etc).
(c) configuration (eg. thin sliver or spherical lump)
(d) orientation (eg. on wall, ceiling or floor)
(e) mode of ignition (ie. position)
(f) type of ignition (ie. flaming or smoldering and temperature)
(g) oxygen availability (whether doors or windows are closed)
(h) rate of air flow
(i) ambient temperature
(j) catalysts (eg. presence of trace metals)
(k) situation (open or corridor where products cannot escape)
(l) presence of flame retardents

Nelson (39) underlines the fact that smoke formation is not an intrinsic material property but is highly dependent on conditions. A good supply of air will often produce near ideal combustion conditions with a hot, low smoke fire, while a poor supply will produce greater smoldering conditions with a high smoke, cooler fire having a small (if any) flame. The complex mechanism of smoke formation from various materials, has been described by Smith (40) and his co-workers at Queen Mary College (41) and by Taylor (42).

Smoke travels in front of a fire and will probably cut off routes of escape by obscuration (by reducing atmospheric visibility or affecting the eyes) or possibly by an unpleasant odour. In a confined fire
(e.g., in a sealed room), smoke can only diffuse to a limited extent and will therefore build up in thickness. In smoldering conditions where thermal decomposition is produced by exposure to radiant heat and perhaps depleted oxygen levels, smoke can form in fairly copious amounts. The build up of flammable gases under these conditions may produce explosive conditions (43).

Rasbach (44) has estimated that soot is unlikely to exceed 10% of the mass of the original material.

Recently, the part smoke plays as a fire hazard has become more worrying, with the large range of materials in use. Firemen often report (42) smoke from fires appearing thicker and more noxious than once experienced, especially in high rise buildings and enclosed shopping precincts. In these conditions vision may be obscured by smoke, therefore people cannot see to escape and will then possibly die from suffocation or toxic gas inhalation rather than the effects of burning.

2.4.1. Test Methods for Determination of Smoke Evolution

The reduction of visibility due to smoke depends on its:

(a) composition
(b) concentration
(c) particle size and distribution
(d) nature of illumination
(e) condition of the observer (usually the eye or a photocell).

To relate to real-life fire situations, the test should produce a measurement which is directly comparable with the average response of the human eye. Photocells which are most often used to measure the
attenuation due to smoke, respond mainly to the infra red spectrum. However no test can compensate for the physiological and psychological response of the visual facilities of a human under fire conditions. The problems of the development and evolution of suitable monitoring are discussed in some details elsewhere (44, 45, 46, 47, 48). Critical reviews of many modern apparatus and test methods are numerous (47, 49), and among the most popular standard smoke tests are:

(a) ASTM D2843/70 (originally the Rohm and Haas XP-2 test)

(b) ASTM E84 Tunnel Test (the longest established test)

(c) Swedish hot box

(d) Dutch flash-over test

(e) BS476 :9

(f) AMINCO NBS smoke test.

In addition large and full scale tests include their own smoke determination apparatus but these are still peculiar to research establishments and large companies (eg. Rubber and Plastics Research Association and Fire Research Station). Recently Queen Mary College have introduced their own design of a smoke rig. These apparatus measure a parameter which is quantified for comparative or legislative reasons, while a few measure a fundamental property, and these must have a standard procedure and defined apparatus construction scrupulously followed.

The bases of most laboratory scale smoke determination apparatus are as follows:

(i) a fixed volume of air in a standard enclosed chamber

(ii) standard sample size (although thickness can vary, as in the AMINCO test)

(iii) sample fixed in a specific part of the chamber, adjacent to the heat source and at a distance from the actual
monitoring equipment

(iv) flame and/or radiant heat ignition source of a fixed calorific emission or heat flux respectively, (the Queen Mary College rig can irradiate samples with heat fluxes between 15 and 75 Kw/m²). Heating output is usually constant during test. Certain of the larger tests have wood cribs to initiate fire

(v) an optico-electronic monitoring system to measure the attenuation of a light beam of fixed length (and usually diameter) and luminosity, positioned inside the chamber itself (eg. AMINCO) or in a separate chamber into which the smoke is drawn (eg. ASTM D2843/70) or at several points along a corridor in the full scale tests. A lamp (normally with a voltage stabilised source, and an optical set up to produce a parallel beam) produces a steady beam of light which, having passed through the monitoring chamber, falls on to a photodetector. The voltage produced in it is amplified and displayed in some manner. The ASTM D2843 test also includes an illuminated EXIT sign at the rear of the main chamber for human assessment of obscuration.

There are two schools of thought as to the positioning of the monitoring equipment. The AMINCO and Queen Mary College tests have, for instance, a vertical light path of relatively great length (ie. 3 feet) to overcome the problem of smoke stratification, but can suffer badly from particle deposition on the exposed parts of the optics. The ASTM D2843 test has a horizontal light path of relatively short length. Yet others have light paths inclined at various lengths.

(vi) some form of extraction system to exhaust the test chamber
or draw smoke into the separate monitoring chamber.

Variations on this basis are met in the tests used to measure a number of fire parameters (e.g., BS 476:9 or ASTM E84 tunnel test). A few tests use non-optical means for measuring smoke. Cass (50) has collected smoke by filtration and expressed it in terms of weight per cent of specimen. The problem that arises is that once values of smoke from a material are obtained, how may they be interpreted in respect of other rigs and real life fires?

Quantitative values of smoke are derived from its capacity to impede the transmission of light. Although percentage transmission is used as a measure, higher levels of smoke are difficult to differentiate between unless determined in terms of neutral optical density (NOD). This closely parallels the human eye response over the middle of the visible spectrum and therefore has significance in relevant smoke measurement. Optical density is the negative logarithm (base 10) of the fraction of light transmitted across a length of smoke path from a standard light source falling on a photo-electric cell (44, 47, 51), ie.

\[ D = -\log_{10} \frac{T}{100} = \log \frac{100}{T} \]

Where \( D \) = optical density, \( T \) = transmittance measured by a photocell.

Providing no change in smoke particle type occurs, Beer's Law (or law of extinction) may be applied, giving a relation between optical density and the product of the light transmission path length (L) and smoke concentration (c).

\[ D = kLc \]

Where \( k \) = a constant depending on type of smoke particle showing optical density is directly proportional to the smoke concentration. Gross et al (47) showed that if smoke is produced from an initial surface area (A) exposed to heat or flame in a sealed
chamber of volume \((V)\), the optical density is directly proportional to \(A\) and inversely proportional to \(V\).

ie. \(D = D_s \cdot \frac{AL}{V}\)

\[
D_s = \frac{V}{LA} \cdot \frac{D}{L}
\]

\[
D_s = \frac{V}{LA} \log_{10} \frac{100}{T}
\]

\(D_s\) is the specific optical density representing the optical density measured over unit path length within a chamber of unit volume, produced from a specimen of unit surface area. It is dimensionless and represents the "smoke density" independent of chamber size, specimen size or photometer path length. It is dependent on specimen thickness, its chemical and physical properties and exposure conditions (ie. radiant or flaming). Specific optical density must be used with due regard to the following limitations:

(a) smoke distribution must be uniform

(b) smoke produced must be independent of the excess air available

(c) the optical density is a linear function of the concentration for any smoke

(d) agglomeration, deposition and other changes in the smoke are similar regardless of specimen size or shape and size of chamber

(e) human and photometric vision, through light scattering smoke aerosols, are the same when expressed in terms of optical density.

The specific optical density unit is limited in use when testing large samples or applied to full scale tests, since heat flux can vary as the area exposed may during test. There is greater relevance in determining a value related to mass loss through burning. This can be simply developed from:
Let the volume of sample $V_2 = WA$

$A = \frac{M}{\rho W}$

$\therefore D_s = \frac{V}{L} \cdot \rho \frac{W}{M} \cdot D$

Seader et al (52) have shown that:

$D_s A = D_m M$

$D = D_m \cdot \frac{ML}{V}$

$D_m = \frac{DV}{ML}$

Most of the apparatus produce the following data:

(a) maximum smoke or neutral optical density

(b) time to maximum smoke density

(c) maximum rate of smoke accumulation.

Lists of smoke evolution data for various materials are given in a variety of reference (eg. 47). At the present time there is considerable work being carried out to correlate smoke data with actual human observation during real fires and hence establish meaningful values from quality control tests (18).

2.5 Toxic Gas Evolution and Its Measurement

In the United Kingdom, of the total number of people who died as a direct result of fire, one half were attributed to the combined effects of smoke and toxic gas, and the remainder were due to burns and other injuries (37). Smoke acts to reduce visibility and so hinder escape, while toxic gases, coupled with oxygen depletion are responsible for most of the deaths. In addition, certain toxic gases at sub-lethal levels along with specific lacrymatory gases, induce severe eye and inhalation irritancy. At relatively low
concentrations, gases become lethal, some being odourless, incapacitate without warning, while others may produce undesired physiological reactions some time after exposure.

Any polymer subjected to an elevated temperature (200°C +) will break down into smaller fragments, volatiles and gases, typical toxic gases released are shown in Table 9.

TABLE 9 : Toxic Products That May Be Obtained from Combustible Materials

<table>
<thead>
<tr>
<th>Toxic Gas or Vapour</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Monoxide or Dioxide</td>
<td>All flammable materials containing carbon</td>
</tr>
<tr>
<td>Nitrogen Oxides</td>
<td>Celluloid, polyurethanes</td>
</tr>
<tr>
<td>Hydrogen Cyanide</td>
<td>Wool, silk, polymers containing nitrogen</td>
</tr>
<tr>
<td>Formic Acid</td>
<td>Cellulosics, including rayon</td>
</tr>
<tr>
<td>Acetic Acid</td>
<td>Wood, paper</td>
</tr>
<tr>
<td>Acrolein</td>
<td>Natural rubber, &quot;Thiokol&quot;</td>
</tr>
<tr>
<td>Sulphur Dioxide</td>
<td>PVC, fire-retarded polymers</td>
</tr>
<tr>
<td>Halogen Acids, Phosgene</td>
<td>Melamine, nylon, UF</td>
</tr>
<tr>
<td>Ammonia</td>
<td>PF, wood, nylon, polyesters</td>
</tr>
<tr>
<td>Aldehydes</td>
<td>PS</td>
</tr>
<tr>
<td>Benzen e</td>
<td>PF</td>
</tr>
<tr>
<td>Phenol</td>
<td></td>
</tr>
<tr>
<td>Azo - bis - Succino Nitrile</td>
<td>Some foamed polymers</td>
</tr>
</tbody>
</table>

These gases in turn may react with other species (eg. among themselves or with atmospheric oxygen) producing a very complex mixture of gases.

The composition of the gaseous products is very dependent on fire conditions (eg. heating rate, temperature, polymer composition, oxygen supply etc.) and in large fires, conditions will vary from
point to point. Under ideal fire conditions with continuous adjustment of the fuel to air composition, complete combustion to carbon dioxide, water and a few other relatively low molecular weight species might be possible. Evidently, this does not occur since large quantities of carbon monoxide are always present in organic fires.

Other gases released are dependent on the parent polymer (and have been used to "finger print" a polymer at fixed pyrolysis temperatures). Nitrogen containing polymers release hydrogen cyanide and various nitrogen oxides during fire. The quantities of hydrogen cyanide released appear dependent on the manner in which the nitrogen is attached to polymer chain, e.g. in order of decreasing stability: polyimides, aromatic nylons, aliphatic nylons, polycrylonitrile, polyurethanes. Some chlorine based polymers will rapidly release large quantities of hydrogen chloride at relatively low temperatures (e.g. PVC). Monomer may be released by a unzipping mechanism (e.g. polyacetal or polymethyl methacrylate). Flame retarded polymer can complicate the situation by releasing certain gases (possibly toxic) as a means of smothering the fire, and may so promote carbon monoxide by their action.

Lists of major gases released in fire by certain polymers are given in several papers (53 to 58). However, these often report analyses carried out under idealised conditions using semi-micro quantities of sample in either inert (pyrolysis) or oxidative conditions, and analysis by gas chromatograph coupled with mass-spectrometer. Wooley has recently reported (59) gas sampling and analysis techniques used in large scale work at the Fire Research Station, and some information has been released by the Inter-Company Urethane Panel on similar work involving upholstered furniture (60).
2.5.1. Toxic Gas Measurement

The main work carried out in the identification and quantisation of gases produced from polymers, relies on chemical analysis, and in particular the determination of the concentration of a single species. These results must be related to the findings of biological-toxicological testing, where animals are exposed to gases and vapours either singly or in mixes from fires or gas cylinders. Often as not, there is no relevant data related to the toxicity of certain gases. However, information is very limited as to what levels of toxic fumes a human will succumb, and these often derived from studies made on workers in their industrial environments or of conditions in which poison gas victims were exposed. Obviously, volunteers cannot be subjected to laboratory tests to investigate these toxicological effects of a vast number of chemicals.

(i) Semi-micro Work.

Work has been conducted into the study of the pyrolysis products from semi-micro quantities of polymer, heated under controlled conditions. Pyrolysis normally takes place in an inert atmosphere (e.g. nitrogen or helium) or under oxidative conditions (e.g. air or oxygen). The material is rapidly heated by either of the following:

(a) solution coated resistance or Curie point wire, electrically heated

or (b) divided polymer in a surrounding furnace.

The degradation products are swept out of the pyrolysis area by an inert carrier gas to a part of the apparatus where analysis can be conducted. This is often carried out in a gas chromatograph linked with a mass-spectrometer. The gas chromatograph separates the pyrolysis gas by adsorption on to a stationary liquid phase, coating the inner wall of a heated column. The de-adsorption rate of each species is related to
the physio-chemistry and separation occurs. As each gas de-adsorbs from the column it passes through a detector and then into a rapid scan mass-spectrometer for identification; analysis may take as little as three seconds for each gas. Data from the gas chromatograph-mass spectrometer can be interpreted by computer-filed library reference giving both a name and quantity present of each gas. A fairly full analysis of the overall gases produced can be achieved by this method.

The extrapolation of semi-micro data to full scale fires has met with difficulty since conditions of pyrolysis are so greatly different. However, Wooley has used the gas chromatograph-mass spectrometer technique for analysing gas samples taken from large scale fires (ie. by injecting the gas straight on to the gas chromatograph). At best, employing this method of gas analysis during fire-test, will give discontinuous information of gas build up (ie. by using a large number of sampling bottles, removed regularly as the experiment proceeds). Gas chromatograph analysis is too slow to allow continuous monitoring.

(ii) Continuously Monitoring Gas Analysers

A number of continuously monitoring analysers, measuring concentration of particular gases are available but are not cheap. Several of the full scale fire test facilities (60) use them but some foresight is required of the major toxic gases present in fire prior to the selection of specific monitors.

The monitoring is fairly easy. Sampling points are set up within the vicinity of the fire and pumps draw the gaseous products through various filters and flowmeters to the analysers, set up either in parallel or series. Typical modes of analysis include the following:
(a) Non-dispersive infra-red analysis. This technique has been described fully by Hill et al (61). The analyser consists of a sample column through which the gas flows, and a sealed reference column containing a known concentration of the gas to be determined. A fixed wavelength of infra-red radiation, specific to the maximum adsorbance of the gas, passes through each column and on to a photodetector. By the use of a beam chopper comparison of the two columns is made electronically, and the concentration of the gas sample is determined. This method has been used to measure continuously carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NOₓ), hydrogen cyanide (HCN) and hydrogen chloride (HCl).

(b) Chemiluminescence. This is used to estimate nitrous oxide (NO) and nitrogen dioxide (NO₂). The filtered gas passes to the analyser and is reacted with ozone to produce nitrogen dioxide. As the reaction is photochemical, light is given off which is detected. The amount of radiation produced is related to nitrous oxide concentration.

(c) Paramagnetic Analysers. This is the cheapest of the continuously monitoring analysers, but can only be used with paramagnetic molecules (eg. oxygen for oxygen depletion). It must be noted that delay exists in analysis, due to the time the gas travels through the piping and then apparatus response.

(iii) Miscellaneous Non-continuous Methods

(a) Colourimetric tubes (eg. Drägers) are used for specific gas analysis where that gas is suspected. The gas or vapour reacts with a reagent within a tube to produce a colour change. The distance along a tube the gas is
absorbed and reacted in (indicated by colour change), is related to the concentration of the gas, (printed on the side of the tube). Typical ranges of measurement of the Dräger tubes are shown in Table 10.

**TABLE 10 : MAC, Immediate Danger to Life Concentrations, with Dräger Tubes Ranged for Some Toxic Gases (62)**

<table>
<thead>
<tr>
<th>Gas</th>
<th>M.A.C. (ppm)</th>
<th>Immediate Danger to Life (ppm)</th>
<th>Boiling Pt. (°C)</th>
<th>Dräger Tube Ranges</th>
<th>Detection Limits Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>50</td>
<td>3000 – 5000</td>
<td>-191.5</td>
<td>10 – 3000</td>
<td>0 – 90</td>
</tr>
<tr>
<td>CO₂</td>
<td>500</td>
<td>10⁵</td>
<td>-78</td>
<td>10⁴ – 2x10⁵</td>
<td>0 – 50</td>
</tr>
<tr>
<td>NH₃</td>
<td>100</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>HCl</td>
<td>5</td>
<td>1000 – 2000</td>
<td>-83.7</td>
<td>2 – 100</td>
<td>0 – 40</td>
</tr>
<tr>
<td>HCN</td>
<td>10</td>
<td>200 – 300</td>
<td>25.7</td>
<td>2 – 150</td>
<td>5 – 30</td>
</tr>
<tr>
<td>NOₓ</td>
<td>5(NO₂)</td>
<td>200 – 700(NO₂)</td>
<td>21.3(NO₂)</td>
<td>0.5 – 10</td>
<td>0 – 50</td>
</tr>
<tr>
<td>HF</td>
<td>3</td>
<td>50 – 250</td>
<td>19.4</td>
<td>0.5 – 15</td>
<td>0 – 40</td>
</tr>
<tr>
<td>SO₂</td>
<td>5</td>
<td>400 – 500</td>
<td>-10</td>
<td>5 – 150</td>
<td>0 – 40</td>
</tr>
<tr>
<td>HCHO</td>
<td>5 – 10</td>
<td>50 – 100</td>
<td>-10.5</td>
<td>2 – 40</td>
<td>0 – 40</td>
</tr>
<tr>
<td>C₆H₅OH</td>
<td>5</td>
<td>----</td>
<td>182</td>
<td>----</td>
<td>----</td>
</tr>
</tbody>
</table>

Key:  + MAC = Maximum allowable concentration for an 8 hour working day  
*ppm = parts per million

The range of tubes is very large, in theory allowing for the analysis of many gases, but the time to draw the required volume of contaminated air through them, limits testing to only a few gases.

(b) Infra-red, elemental and wet analysis:

By employing an evacuated sampling bottle (opened to the contaminated atmosphere at a desired time) or a cold trap (cooled by liquid nitrogen or solid carbon dioxide, depending on the boiling points of gases to the sampled), single
analyses of gas mixes per test can be made. Along with gas chromatograph suggested above, infra-red analysis can be carried out by injecting the gases into an infra-red cell and hence establish the molecular species present. Elemental analysis can be used to determine the ratios of elements present (eg. carbon, hydrogen, oxygen, nitrogen, sulphur and chlorine). In addition, standard analysis can be attempted for specific compounds (eg. isocyanate analysis as detailed in Appendix 4), which are listed in most good organic analysis text books (64).

2.5.2. Toxicological Assessment

Even when armed with details of toxic gas concentrations present in polymer fires, toxicologists are still unsure of how a human will physiologically (and mentally) react to that gas exposure. So much data relates to the effect of single gases during a working day's exposure (ie. maximum allowable concentration or MAC for an 8 hours value). Little is known of the effect of short term exposures of gases not especially regarded as highly toxic, and also of what levels will kill after a short exposure, particularly of gases in combinations (eg. might synergism occur), and what is the long term affect of those low concentrations of higher molecular weight gases (eg. possible carcinogens) if a person survives the fire.

All this would be relevant to firemen who are exposed to fire on many occasions.

A paper by Autian (53) on the toxicological aspects of flammability and combustion of polymers, describes and discusses the whole spectrum of information related to this subject. This paper details the toxicological
and physiological effects of gases and fumes, laboratory experiments on animals and suitable reference on the subject. At a conference in Edinburgh, some information was given on the animal studies on toxic gas synergism (63). Synergism may be partly attributed to certain gases (e.g. hydrogen cyanide) which induces a panting reaction in humans so that more toxic gas is inhaled into the body at an increased respiratory rate.

At the moment toxicological work is still at an early stage of studying burning polymers, since the subject is complex and therefore somewhat time consuming and expensive.

2.6 Heat and Temperature Generated by Fires

Heat is generated during a fire from depolymerisation, pyrolysis and oxidation reactions, so atmospheric temperature increases. Once again heat evolution is related to the type of material and fire conditions; heat in turn may cause ignition conditions in surrounding area promoting fire spread. Temperatures of up to 1200°C have been recorded in burning warehouses containing polyurethane, causing structural damage to the building (e.g. melting of steel girders!).

When heat or temperature change has been measured, thermocouples or, occasionally, optical pyrometers are used, usually in the immediate vicinity of the fire and at points of probable escape.

Thermal studies of semi-micro quantities of polymers (non-composite forms) are carried out using differential thermal analysis, thermogravimetric analysis and other thermal analysis equipment. Information of glass transition temperature, melting point and weight loss with rise in temperature can be determined by this means.
2.7 Physiological and Psychological Aspects of Fire

An increasing number of fatalities due to fire are due to smoke and toxic gases present, eg. in the United Kingdom in 1964, 53% died of burns, in 1972 more than 50% of deaths in fire were due to toxic gases and smoke inhalation. Over the period 1960 to 1966, 40% of the burn fatalities were rendered unconscious by carbon monoxide.

Trapped in the area of a fire a person may undergo several biological reactions, which are deleterious to the ability of the subject to escape, eg.

(a) panic due to being exposed to such a situation
(b) loss of vision due to smoke obscuration and lacrymose gases
(c) physiological effects due to the inhalation irritants and toxic gases
(d) psychological effects resulting from (a), (b) or (c).

In trying to establish the extent of these effects on humans, work has been limited to requesting surviving victims to fill in questionnaires listing as many relevant questions about the fire as possible. Full post-fire medical examination including blood, urine, etc. samples are also of value in establishing statistical physiological data from fire victims.

Whether a person surviving a fire will be later affected by toxic gases depends on:

(a) quantities and types of gases inhaled
(b) his physical and mental ability to overcome the effects.

Fire itself causes:

(a) burning to the skin with very painful effects which destroys layers of the epidermis. Skin repair may have to be left to time and nature, or alternatively, skin-grafting from other parts of the victim's body. Even so, unpleasant
disfigurement may result
(b) hot air inhalation, even at temperatures as low as 60°C
can cause lung dehydration and partial collapse, interfering
with oxygen transfer into the blood stream, and causing
respiratory difficulties.
The aftermath of a fire may produce psychological effects, eg:
(a) adverse mental reactions when clearing fire damage
(b) shock from possible bereavement
(c) living with scars.
The possible exposure of human life to these many associated dangers
of fire, demands that strong and definite steps should be made
to fully understand how polymers act in fire conditions and methods
of producing non-flammable polymers, or precisely classifying the
fire aspects of polymers.
CHAPTER 3: ACTION OF POLYURETHANES IN A FIRE ENVIRONMENT
3.1. An Outline of Polyurethane Foam Process

Polyurethane (PU) is the name describing a wide range of polymers which contain the urethane linkage, ie.

\[
\begin{array}{c}
\text{H} & \text{O} \\
\text{H} & \text{N} - \text{C} - \text{O} \\
\end{array}
\]

The variety of types of plastics, rubbers and resins containing this grouping stem from the vast number of parent chemicals that can be used to make the polymer, ie.

\[
\text{R'OH} + \text{R'NCO} \rightarrow \text{R} - \text{N} - \text{C} - \text{O} - \text{R'}
\]

Typical reactants are described below.

A number of side reactions also occur during the formation of the polyurethane. The detailed chemistry and properties of polyurethanes are discussed in great detail in many text books and technical literature (eg.64). The manufacture and nature of polyurethane flexible foams will only be described here.

The largest percentage of the cellular plastics market in the United Kingdom for 1971 was held by polyurethane foams, and all indications are that they will increase their share in the future. This is shown in Table 11. Table 12 shows the relative popularity of upholstery fillings in the United States for the period 1966 to 1970.
TABLE 11: Estimated Usage of Cellular Plastics

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Use</th>
<th>Weight used in UK in 1971 (x 1000 tonnes)</th>
<th>Weight used in US in 1974 (x 1000 tonnes)</th>
<th>Estimated use in US by 1978 (x 1000 tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible PU</td>
<td>Furniture</td>
<td>12.0</td>
<td>180</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>Transport</td>
<td>11.0</td>
<td>170</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>Textiles</td>
<td>6.0</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Household</td>
<td>5.0</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Bedding</td>
<td>3.0</td>
<td>60</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>Packaging</td>
<td>1.6</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Rug Underlays</td>
<td>--</td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Misc.</td>
<td>2.4</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>40.0</td>
<td>460.0</td>
<td>705.0</td>
</tr>
<tr>
<td>Rigid PU</td>
<td>Refrigerators</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Containers</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Others (eg. furniture)</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>8.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>Building &amp;</td>
<td>5.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cold store</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Packaging</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Retail (eg. tiles)</td>
<td>4.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Misc.</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>15.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: In addition small amounts of other polymers are used.


<table>
<thead>
<tr>
<th>Material</th>
<th>Weight Used(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU Foam</td>
<td>34</td>
</tr>
<tr>
<td>Latex Foam</td>
<td>33</td>
</tr>
<tr>
<td>Cotton Felt</td>
<td>20</td>
</tr>
<tr>
<td>Hair</td>
<td>10</td>
</tr>
<tr>
<td>Dacron</td>
<td>3</td>
</tr>
</tbody>
</table>

There are two major classes of polyurethane foam, the flexibles and rigids. Linear or slightly crosslinked polyurethanes, based on high molecular weight polyols are used to produce the former and highly crosslinked
polyurethanes with low molecular weight polyols the latter. Flexible polyurethanes are used extensively for cushions in furniture and automobiles, having largely displaced latex foams and the other traditional fillers because of their improved comfort, strength, lower density (and hence reduced weight), long term dynamic properties and easier processing.

Foamed polyurethane is usually produced by the addition of a controlled quantity of water to the reactants. The water, acting as a blowing agent, reacts with excess isocyanate to produce carbon dioxide which bubbles through the polymerising mass, ie.

\[
R''\text{-NCO} + H_2O \rightarrow \left[ \begin{array}{c}
R''\text{-NOH} \\
\text{H}
\end{array} \right] \rightarrow R''\text{-NH}_2 + 2CO_2
\]

This reaction has been superceded by the inclusion of a low boiling point pneumatogen (eg. 'Arcon' 11 or 'Freon' 11, a trichlorofluoromethane), which vapourises when the reaction starts to exotherm. The final structure and properties of the foam are affected by the balance of reactants used.

Flexible polyurethanes based on prepolymers derived from 2,4 and 2,6 tolylene diisocynate (TDI) and polyester polyols are more widely used in the United States than in Britain. The one-shot foam process (68) is more commonly used in the United Kingdom. Here polyether polyols (usually produced by alkoxydation of ethylene or propylene oxide) are directly reacted with either TDI or 4,4'diphenyl diisocyanatomethane (MDI). The polyol is blended with catalysts (commonly amines and/or lead or tin organic complexes) to give rapid urethane and foam formation. A surfactant (eg. silicone oil) may be added as finely dispersed droplets, which act as nucleating sites, gives a uniform cell structure. Water and flame retardants may also be added. This polyol mix is placed into a stirred sealed tank at a controlled temperature. The isocyanate is placed into another temperature-controlled tank. A third tank may be used to contain any liquid blowing agent, if blending with the isocyanate is not desired.
The tanks are pressurised with dry air or nitrogen to force-feed the ingredients to a mixing head via metering pumps, which give the required stoichiometric ratios. Mixing at the head is usually carried out with a high speed mechanical stirrer.

The blended reactants are forced under pressure from the mixing head into a trough on a moving conveyor belt, with the head oscillating at right angles across the width of the trough to give uniform fillings. The blowing and polymerisation are completed in the trough to give a "loaf" of foam. This process is known as slab stocking. Alternatively, the blend of reactants, of known shot size can be fed into a heated mould to give a shaped cushion; this is favoured by the manufacturers of cold or hot cure polyurethane systems, especially in the motor industry. The continuous slab stocking technique is used to yield foam up to two metres wide and 1.5 metres high. The "loaf" is cut up into 3 to 20 metres lengths and after postcuring and cooling for 10 to 24 hours at room temperature, it is further cut up for sale to fabricators. At any cutting stage where dust and crumb accumulate and where foam is stored, there is an increased risk of fire danger. These possible industrial flammability problems are cause for great concern and are discussed in detail elsewhere (66, 69).

There are four major types of flexible polyurethanes used in furniture in the United Kingdom nowadays, namely:

(i) standard foam: usually TDI - polyether based foam
(ii) fire retarded foam: standard foam with addition of fire retardants which tend to reduce certain of the mechanical properties of the foam
(iii) high resilience foam: foam usually formed by cold cure methods. The chemistry is modified (by the use of certain catalysts and curing techniques), to lower the melting point of the parent polyurethane

(iv) neomorphic foam: foam whose chemistry is fundamentally changed, so that thermal decomposition takes place well below the temperature of ignition of the foam.

Typical densities of polyurethane foams are 1 to 60 kg/m$^3$; flexible cushioning foams are in the order of 20 to 35 kg/m$^3$. Seating foam is typically 30 kg/m$^3$ and chair back foam 20 to 25 kg/m$^3$.

3.2 The Action of Fire on Polyurethanes

Polyurethane foams have been accused of being the major cause of fires and fire spread in the home, thus there has been considerable study of the reaction of polyurethane to high temperature and fire conditions. The thermal decomposition of polyurethanes in an inert atmosphere is reported in a number of papers (70) and probably follows these mechanisms:

(i) Thermal dissociation of the urethane to the isocyanate and alcohol:

$$RNHCO\_H' \rightarrow RNCO + H'OH$$

(ii) formation of a primary amine, olefin and carbon dioxide:

$$RNHCO_2CH_2CH-K'-K'' \rightarrow RNH_2 + CO_2 + K'-K'' = CH_2$$

(iii) formation of a secondary amine and carbon dioxide:

$$RNHCO_2 H' \rightarrow RNHR' + CO_2$$

(iv) possibility of isocyanate reacting further, eg:
These reactions are reported to be typical of the depolymerisation of TDI based polyurethanes. Wooley (56 to 58) has made detailed studies of the semi-micro pyrolysis of various polyurethanes at various temperatures. He showed that TDI based polyester and polyether flexible foams have a preferential loss of a nitrogen rich material, and at 300°C there is virtually complete loss of nitrogen from the polymer (weight loss corresponding to 30%). This nitrogen rich material has been called a "yellow smoke", (due to its appearance in laboratory tests), and has been shown to be the dimers or trimers of TDI. (TDI has associated toxicological properties, e.g. eye irritant, respiratory and bronchial hazard, and inducing asthmatic type conditions at concentrations as low as or lower than 0.02ppm). Fortunately conditions exist in polyurethane fires that minimise the effect of evolved TDI, e.g. water vapour reacting with it, or thermal dissociation. The yellow smoke decomposes readily above 800°C and completely by 1000°C, giving lower molecular weight nitrogen based compounds, the predominant species being hydrogen cyanide along with acetonitrile, acrylonitrile, pyridine and benzonitrile, (all of which are toxicologically hazardous). Yields of hydrogen cyanide increase with temperature, and at 1000°C approximately 70% of the theoretically available nitrogen is released. MDI based foams, in not passing through a yellow smoke stage, lose approximately 40% of total nitrogen
at 500°C and up to 100% at temperatures above 500°C, at which hydrogen cyanide may also be released (70).

The nature of thermal degradation becomes extremely complex under oxidative conditions. In addition to reactions stated above the following may occur:

(i) degradation of bonds other than urethane present in the polymer chain (eg. degradation of the ether or aliphatic groupings)

(ii) reaction between the host of degradation products and oxygen

(iii) the completeness of burning affecting amounts of carbon monoxide released.

Cellular polymers more readily undergo oxidative thermal degradation, than their unfoamed polyurethane equivalents since there is:

(i) a ready supply of oxygen on hand from within the structure of the foam. (Note: the blowing agent is replaced by air between one and seven days after manufacture)

(ii) a relatively greater surface area of polymer exposed to any flame.

Typical combustion products from a polyurethane foam used in automobile seating and carpet backing is shown in Table 13.
TABLE 13: Combustion Products of Polyurethane Seating Foam (28)

<table>
<thead>
<tr>
<th>Air Flow (cc/min)</th>
<th>100</th>
<th>100</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen Flow (cc/min)</td>
<td>0</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Heating Rate (°C/min)</td>
<td>5</td>
<td>5</td>
<td>50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gases produced (mg/g)*:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>712</td>
<td>661</td>
<td></td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>193</td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>Nitrile (as Hydrogen Cyanide)</td>
<td>46.2</td>
<td>34.6</td>
<td>19.3</td>
</tr>
<tr>
<td>Ammonia</td>
<td>1.6</td>
<td></td>
<td>0.24</td>
</tr>
<tr>
<td>Methane</td>
<td>1.73</td>
<td>2.02</td>
<td>21.2</td>
</tr>
<tr>
<td>Ethylene</td>
<td>1.95</td>
<td>3.55</td>
<td>16.9</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.18</td>
<td>0.6</td>
<td>3.9</td>
</tr>
<tr>
<td>Propylene</td>
<td>2.31</td>
<td>10.55</td>
<td>67.3</td>
</tr>
<tr>
<td>Propane</td>
<td>0.22</td>
<td>0.6</td>
<td>7.3</td>
</tr>
<tr>
<td>Methanol</td>
<td>13.2</td>
<td>9.3</td>
<td>6.6</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>17.7</td>
<td>20.5</td>
<td>10.2</td>
</tr>
<tr>
<td>Propionaldehyde</td>
<td>7.2</td>
<td>13.7</td>
<td>7.8</td>
</tr>
<tr>
<td>Dimethyl Ketone</td>
<td>13.6</td>
<td>14.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Nitrogen Accounted for (%)</td>
<td>53.3</td>
<td>37.8</td>
<td>21.1</td>
</tr>
<tr>
<td>Foam Accounted for (%)</td>
<td>38.3</td>
<td>37.8</td>
<td>17.3</td>
</tr>
</tbody>
</table>

Sample (0.5 to 2g) containing 4.74% nitrogen

* proportion of total gas produced.

Uncovered polyurethane foams on exposure to fire, are readily flammable and support combustion due to the decomposition products produced.

Under the same circumstances fire-retarded polyurethanes and polyisocyanurate based foams have a degree of fire resistance.

Wong (71) pyrolysed several types of polyurethanes in air, and collected the decomposition products from cold traps of differing temperature. Using infra-red analysis it was shown dangerous quantities of carbon monoxide, hydrogen cyanide, isocyanate and amine may be present when most polyurethanes are degraded, while fire retarded polyurethanes produced in addition hydrogen halides and some phosphorous based compounds. Carbon monoxide was present as the main toxic gas measured.
In the toxicological comparison of gases evolved by some polymers, Zapp (72) pyrolysed three polyurethanes, natural rubber, neoprene and PVC foams of comparable weights and at three temperatures in glass tubes, exposing rats to the air that passed through the tube. Under these confined conditions, the polyurethanes produced the lowest mortality rates. Mortality for the polyurethanes was higher at 250°C, (with 40% weight loss from the foams), than at 500°C (with complete weight loss). It has also been shown that the polyurethane pyrolysis products (i.e. heating alone, and presumably under smoldering conditions) are more toxic than the combustion products (i.e. heating and burning by flame). It has been estimated 1 lb of polyurethane pyrolysed in 250 cubic feet of air would prove lethal to man within 30 minutes without any appreciable air change; this is similar to the effect of PVC. The toxicity study of polyurethane is complicated by:

(i) the presence of any halogenated hydrocarbon (e.g. blowing agent) degrading to phosgene

(ii) high smoke levels, when solid smoke particles may retain irritants by the action of surface adsorption.

The reason for rapid smoke formation from polyurethane foams may be speculated from their open cellular structure. This openness allows large and rapid breakdown of the polyurethane to condensates and gases and the remaining foam as a char lacks any physical strength, has poor bonding with neighbouring cells and low mass, and therefore rapidly breaks away as sooty particles travelling on thermals.

In any comparison of polyurethane and latex foams or flock fillers, each has associated fire hazard:

(a) polyurethane burns with rapid spread of fire and release of heat
(b) latex or flock smolder rather than ignite into flame, producing copious quantities of smoke and toxic fumes. The danger is enhanced since normally a relatively greater mass of either of these two is used in comparison to the polyurethane. These modes of burning are complicated by the addition of fabric coverings on furnishing compositions.

Work has shown that even in a good circulation of air rapid combustion of polyurethane foam will cause oxygen concentration to rapidly fall below the level needed to support life (69). Temperatures in excess of 1000°C have been recorded in fires involving large quantities of polyurethane foam (eg. in warehouses), and "self-extinguishing" high resilience foams produced 1200°C at ceiling height. Because of the dangerous rates of fire spread in these conditions, lives were often lost.

3.3 Fire Retardency of Polyurethane Foams

The problem of poor resistance to fire of normal polyurethane foam is reflected in the amount of research and development carried out, to produce a new grade of polyurethane with improved fire retardency.

Increased thermal stability and hopefully fire resistance can be introduced by either internal or external fire retardency:

(i) Internal fire retardancy, ie. by the introduction of either thermally stable groupings in or to the chain, or thermally unstable groups. The unstable grouping in the polymer will preferentially absorb energy and fragment from the polymer chain as non-flammable gases, leaving a heat impervious surface char. Polyurethanes have been modified by the inclusion of phosphates into the polyol segment
of the chain, with some consequent loss of mechanical properties. Over the last five years cold-cure or high resilience foams have been introduced commercially. The polyurethane derived is partially crosslinked, by the employment of MDI with TDI, and certain catalysts to produce some thermally stable rings in the polyurethane chain, e.g. isocyanurate, or methacrylimide:

![Polyurethane structure](image)

The structure of the polyurethane chains is disrupted by crosslinking or rings, and hydrogen bonding is lost. Hence the melting point is reduced, and when the foam is exposed to small heat sources the polyurethane tends to melt and run away. In the presence of a large fire the early melting of the foam may aid flame spread.

A third alternative is the neomorphic foam. In fire the polyurethane decomposes below the temperature of ignition, contributing to energy loss. It is reported that even when ignited the burning rate is lower, the smoke emission somewhat less and there is a reduction in the level of toxic gases produced when compared to other polyurethanes (13). The decomposition product tends to form globules causing a reduction of flow (cf. high resilience foams). The main disadvantage of the neomorphic foam is its poorer mechanical properties.

(ii) External fire retardancy, i.e. by the introduction of a separate fire retardent during the compounding of the polyurethane ingredients immediately before foaming. The fire retardant can act as follows:
(a) melting below the ignition temperature of the polyurethane forming a glaze, sealing against further oxygen ingress

(b) preferential breakdown during the early stages of the fire, producing inert fire-snuffing gases (and increasing smoke levels), and absorbing energy in this manner

(c) formation of an intumescent barrier on the surface, which when subjected to fire produces a thick heat impervious, inert skin on the surface of the polymer.

A large number of studies of different polymers indicated that compounds containing the elements phosphorous, chlorine, bromine or antimony (as the pentoxide) in the presence of halides, acted as fire retardents. Phosphorous and halogen-based compounds are most commonly used to fire retard polyurethanes. These treatments do make it more difficult to ignite polyurethane foams (reducing the proportion of flammable gases released), when exposed to small fire sources. However, once alight, particularly in large fires, fire retardent based polyurethane foams burn faster than conventional foams, producing large increases in smoke and toxic fumes. This again may be explained by the disruption of polyurethane chains at a molecular level, and hence loss of hydrogen bonding by the plasticising action of the fire retardent.

It has been found that all fire retardents tend to increase the amount of residual char at the expense of combustible vapours. Papa (73) has reviewed a large number of papers related to type and mechanism of fire retardents used with polyurethane foams. In this summary an ideal fire retardent for polyurethane foams must:
(a) be economic
(b) not cause foam scorch
(c) have fire retardant permanence in the polymer
(d) have low viscosity for ease of mixing with the polyol
(e) be compatible
(f) be stable to hydrolysis
(g) minimise the effects of fire, reducing smoke and toxic gases evolved
(h) non-deleterious to the mechanical properties of the foam.
CHAPTER 4: FABRICS AND FIRES
In this programme, some of the work involved the examination of the reaction of foam-fabric composites to fire. Past research on the fire problems of these compositions is discussed in Chapter 5, whilst here a brief description of the fabrics is given.

Woven cloths are popularly used to cover seating foams, along with plastic sheeting acting as imitation leather (eg. plasticised PVC or polyurethane on cotton scrim), and some real leather covering. The materials selected for domestic seating covering have to be:

(a) hard wearing
(b) resistant to a large number of possible household conditions
(c) comfortable
(d) decorative (maintainable over the life of the furnishing)
(e) drape well
(f) give physical strength by covering an otherwise ugly and poor strength flexible interior filling (eg. especially to tear).

Fabrics used are most often based on natural fibres (eg. wool, cotton), synthetic 'thermoplastic' fibres (eg. acrylics, polypropylene, nylon), or synthetic 'thermoset' fibres (eg. cellulose acetate, phenolics). Most of these fibres have little or no fire resistance, and will burn with varying degrees of intensity dependent on their compositions. A newer and more expensive generation of fibres are being developed based on high temperature and "ladder" polymers (eg. aromatic nyons - 'Nomex', modified phenolics - 'Kynol', fire retarded viscous rayon - 'Darelle'). A cheaper means of producing fire retarded fabrics is the introduction of external fire retardents. Typically these are based on modacrylics, wool or cotton treated with a cheap but wash-proof fire retardent, (eg. certain zirconium salts).
The majority of non-fire-retarded fabrics are slow burning (particularly wool), which can delay spread of fire to the bulk of the filler.

Toxic gases produced from burning fabrics include carbon monoxide, hydrogen cyanide from wool, silk and polyurethane, and hydrogen chloride from PVC.

In small scale fire tests it has been found important to examine both the warp and weft directions of weave in the cloth in the direction of burn, since flammability characteristics can vary enormously between the two. This can be particularly true with fabric mixes (eg. one fibre type in the warp and another in the weft direction).
CHAPTER 5: THE ROLE OF POLYMERS IN DOMESTIC FURNISHING FIRES
It is a short step from the vehement attack made on the fire characteristics of polymers by the press, to the industry and research organisations concerned, receiving grants and starting research to determine if their products are as unsatisfactory as the accusations would have us believe. At the present time, requirements for foams and fabrics are limited to certain small scale fire tests, if any, prior to leaving the manufacturers. Over the last six years a great deal of work has been carried out to examine the role of domestic furnishings in fires, since the small scale tests often proved unreliable. This examination has been concerned with the full scale testing of actual items of furniture, large scale testings of large pieces of material, or scaled down testing of typical composites. In full scale tests there is the advantage of carrying out actual fires with real items of furniture, with the opportunity of observing unforeseen fire interactions. However, full scale tests are expensive and hopefully the cheaper, new and improved small scale tests will prove relevant in screening potentially hazardous materials whether in composition or as single items.

5.1 Inter Company Urethane Panel/RAPRA Full Scale Work

The research described in the later chapters of this thesis, stems directly from the Inter Company Urethane Panel work conducted at the Rubber and Plastics Research Association’s (RAPRA) fire test facility at Shawbury, and later at the Fire Services Technical College at Moreton in Marsh.

The work is essentially in four parts:

(i) RAPRA I Tests (60, 79)
FIG 3a: THE RAPRA FIRE TEST BUILDING

PLAN VIEW OF FIRE CHAMBER

FIG 3b: POSITION OF FURNITURE IN FIRE ROOM (PLAN)

FIG 3c: CONSTRUCTION OF FURNITURE

A 180 x 60 x 25 cm - HIGH DENSITY FOAM
B 60 x 60 x 12 cm - HIGH DENSITY FOAM
C 60 x 60 x 12 cm - LOW DENSITY FOAM
D 60 x 60 x 10 cm - LOW DENSITY FOAM

X = IGNITION POINT

FIG 3: RAPRA FIRE TEST SET UP
FIG 3 (cont.)

**FIG 3d:**
POSITION OF THERMOCOUPLES IN FIRE ROOM

- Height Above Floor:
  - 1
  - 2
  - 3
  - 4
  - 5
  - 6
  - 7
  - 8
  - 9
  - 10

- Ceiling Height: 2.45 m

*Oxygen - Probe 0.9 m above floor 2.1 m from corridor wall*

**FIG 3e:**
THERMOCOUPLES AND GAS SAMPLING POINTS IN CORRIDOR TO FIRE CHAMBER (SIDE ELEVATION)

- To after burner
- 0-6 m, 1-2 m, 1-8 m, 1-2 m, 1-2 m, 1-4 m
The influence of upholstery filling materials on the burning properties of simulated three-piece suites was examined. The suites consisted of a settee and two armchairs built on wooden frames (to minimise additional fire load). See Figure 3 for positioning of the suite in test facility and positioning of monitoring sampling positions. Each frame supported a seat and backing cushions (one of each in each armchair, three of each in the settee), giving a total volume of foam of 0.39m³. The suite was placed in a room with a side corridor running from it. Fillers included conventional polyurethane (NFR), high resilience polyurethane (HR), fire retarded polyurethane (FR), latex (L), rubberised hair (RH), woollen flock (WF), covered by fabrics based on either wool (W) or cotton-acrylic (C/A) fibres. Fires were started by a lighted newspaper placed on the central cushion of the settee (see Figure 3). The following fire parameters were then monitored:

(a) temperature rise by thermocouple
(b) toxic gas sampling (carbon monoxide and dioxide, hydrogen cyanide and chloride, nitrous oxide, nitrogen dioxide, sulphur dioxide, TDI and oxygen depletion)
(c) smoke detection.

The rate of flame spread across the furniture was measured, and for a given fabric, heat of evolution decreased in the order:

L NFR HR FR RH WF

and the rate of smoke and toxic gas evolution decreased in the order:

L FR NFR HR RH WF

The latex foam proved to be by far the most dangerous upholstery filling and woollen flock the least dangerous. Of the four foams the high resilience was the least dangerous. While burning, fire retarded produced smoke, carbon monoxide and hydrogen cyanide more rapidly
**Fig 4a:** Plan Of Test Facility

**Fig 4b:** Plan Of Test Room

**Fig 4c:** Thermocouple Positions

**Fig 4d:** Gas Sampling Positions

**Fig 4:** RAPRA 2 TEST SET UP
than the other polyurethane foams. For any given filler, wool covered furniture burned more slowly than the cotton-acrylic covered furniture.

(ii) RAPRA II Tests (74, 79)
The effects of a large number of covering fabrics in combination with conventional polyurethane foam (ie. the most common upholstery filling) were examined. RAPRA I tests showed that a similar fire load ranked the behaviour of foam/fabric combinations, and therefore two chairs, each with seat, back and two arm rests were used (see Figure 4). The total weight of foam was 6.7 kg (volume = 0.24m$^3$) and the weight of the fabrics ranged from 1.3 to 6.8 kg. The left hand chair was ignited in its left hand corner by means of three sheets of a popular daily newspaper; flame flashover to the right hand chair was measured.

Results showed that the rate of flame spread across and heat evolution from the burning chairs were both higher for thermoplastic covers (eg. polypropylene, PVC or nylon), than non-thermoplastic fabrics (eg. cotton, wool). The thermoplastic fabrics when subjected to radiant heat peeled or shrivelled back to expose the unprotected foam. Smoke and toxic gases were rapidly released from chairs covered in acrylic, modacrylic or PVC. The least hazardous fabrics included cotton/acrylic and wool.

A resumé of some of the results is shown in Table 14.

(iii) RAPRA III Tests (73, 75)
A third series of tests developed from the findings of RAPRA II, set out to attempt the following objectives:

(a) the possible reduction of fire hazard in furniture, based on conventional polyurethane and a thermoplastic fabric, by the insertion of a protective interlayer

(b) to determine if this method would also improve the fire resistance in other polyurethane foams and non-thermoplastic fabrics.
<table>
<thead>
<tr>
<th>Composition</th>
<th>Ignition</th>
<th>Flame Spread to Cushion</th>
<th>Flame Spread to Armchair</th>
<th>Temperature Max to 100°C</th>
<th>Smoke 10 - 90% Obscuration to Mid-height</th>
<th>CO Max time to 1500 ppm</th>
<th>NO Max time to 100 ppm</th>
<th>HCN Max time to 100 ppm</th>
<th>HCl Max time to 100 ppm</th>
<th>SO₂ Max as Phenol CO Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFR-wool</td>
<td>***</td>
<td>***</td>
<td>**</td>
<td>**</td>
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<td>*</td>
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</tr>
<tr>
<td>NFR-cott/ac</td>
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</tr>
<tr>
<td>FR-wool</td>
<td>***</td>
<td>***</td>
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<td>*</td>
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<tr>
<td>FR-cott/ac</td>
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<td>***</td>
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<tr>
<td>MR-wool</td>
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<tr>
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<tr>
<td>WT-cott/ac</td>
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<td>***</td>
<td>*</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

- Rapid: <4 min, <10 min, >700°C, <4 min, <3 min, >1500 ppm, <10 min, >100 ppm, <10 min, >100 ppm, <10 min, >100 ppm, >100 ppm, >5 ppm
- Medium: 4-7 min, 10-25 min, 300-700°C, 4-9 min, 3-5 min, 50-1300 ppm, >10 min, >10 min, >10 min, >10 min, >10 min, >10 min, >10 min, 2-5
- Slow: >7 min, >25 min, <300°C, >9 min, >5 min, <40, not reached, >80 ppm, not reached, >60 ppm, not reached, >50 ppm, <1 ppm
Cotton cloth, either untreated or flame retarded with an ammonium bromide-urea mix, was selected as the interlayer material. The experimental set-up was as described in RAPRA II.

Results showed nearly all combinations in the presence of a fire retarded cotton interlayer reduced the rate of flame spread by a factor of three, polypropylene fabric being the exception. For the non-fire retarded interlayer, flame spread was decreased by a factor of 1.5. The times for temperatures, smoke and toxic gas concentrations to reach a dangerous level, also increased by a similar factor. For a given cover and interlayer, rates of flame spread decreased in the order:

\[ L \quad NFR \quad FR \approx HR \]

Latex and fire retarded foams produced carbon monoxide and smoke most rapidly.

Additional tests using cigarettes and methenamine pills as ignition sources, showed a fire retarded interlayer reduced the ease of ignition in the domestic seating composition.

(iv) Moreton in Marsh Tests (79)
Here total system burns were carried out in the furnished lounge of a four bedroom house. The experiments set out to:

(a) identify the main hazards present in a lounge or bedroom after the contents of a typically furnished lounge started to burn;

(b) compare the fire hazards of conventional polyurethane and woollen flock.

The following comments resulted:
(a) smoke and irritating concentrations of hydrogen chloride were generated from the PVC seat covers, making the lounge untenable within a few minutes

(b) the main hazard to life in the lounge was due to the rapid increase in temperature, which would cause unconsciousness after 5 minutes; carbon monoxide, hydrogen chloride, oxygen depletion and smoke levels would make escape difficult

(c) in the bedroom immediately above the lounge, survival for up to an hour would be possible, since the fire spread was limited to the lounge, with smoke, carbon monoxide and hydrogen chloride being the main hazards; hydrogen cyanide was present in less dangerous levels than carbon monoxide

(d) maximum lounge ceiling temperatures were 470°C (cf 1200°C maximum recorded in bulk storage)

(e) TDI was never found above 0.02ppm (cf the value of 200ppm predicted from laboratory tests)

(f) polyurethane foam was more dangerous than woollen flock, especially in comparing rates of temperature increase.

Conclusions that also arose from the findings of these four pieces of work were that the conventional polyurethane foam hazard in domestic furniture was greatly exaggerated. It was suggested that the main reason for this, was that temperature and toxic gas levels were often quoted from bulk storage fire data or from extrapolation of certain laboratory tests.

5.2 RAPRA/FIBS WORK

A precis of a Building Research Establishment report on this work (CP 21/76) is found in a recent New Scientist (17). The findings of the report are most scathing on the subject of the fire safety of modern furnishing materials (eg. polyurethanes or latex), especially when
these are compared with the traditional furnishing materials (eg. woollen flock). The report is also far more critical of polyurethanes than the Inter-Company Urethane Panel. Using similar experimental conditions as those described above in RAPRA I and II, conclusions were as follows:

(a) traditional soft seating, (ie. that which incorporated only cotton/wool wadding, hair or coiled springs) was difficult to ignite, then only burnt slowly with minimum fire spread. Often however, the furniture smoldered for some time before bursting into flame.

(b) semi-modern and modern furniture (ie. containing latex or conventional polyurethane foam) burnt in two stages, first the foam upholstery burnt rapidly producing considerable heat and smoke, then the burning spread the fire to the wooden frame and other furniture in the vicinity. Fires involving modern furniture destroyed all the furnishings. Comment is made that "escape from the fire would have to be more rapid than that from traditional furniture"

(c) traditional interior sprung mattress covered by a woollen blanket, flamed for a few minutes, went out but smoldered and then burst into flame again; the whole fire lasted for two hours and was restricted to the bed.

(d) modern foam mattress burnt more rapidly, with high temperatures (400°C at ceiling level), giving less time for escape. This type of mattress in a simulated bed-sit burnt with considerable production of smoke, and destroyed all the furniture in the room.

(e) there are difference between this work and that of the Inter-Company Urethane Panel, but both agree that the right selection of filler and fabric vastly improved fire.
resistance in domestic furnishings.

5.3 Large Scale Fire Research Station Work

In addition to studying full scale fires developed in public places (e.g. shopping mall simulations), the Fire Research Station has studied large scale fires in materials placed in experimental fire compartments. A typical compartment consists of a room, with a variable ventilation door leading on to a corridor. It was designed to represent a fire situation occurring in a room adjacent to an escape route. The rig can be loaded with any number of polymeric forms, and is fully instrumented to monitor resultant fire parameters; fire can be initiated with a burning wooden crib. This has been used in basic research, e.g. the examination of polyurethane reactions to fire (76).

Recent work has been carried out at the Fire Research Station on the effects of fire in hospital bedding and this work has been reported at recent fire conferences and by Wooley et al (77). Its main conclusion is that careful selection of bedding materials improves fire resistance.

Wooley has carried out other work of interest (43), on the explosion risk of certain foams in fires. This research stemmed from a fire occurring in a store room containing foamed rubber mattresses, which lead to an explosion of previously unknown type, causing two deaths and serious injuries. It was shown that smoldering latex foam produced flammable smoke and vapour, which had a serious explosion risk in confined spaces.
5.4 Other Full Scale Fire Research and Modelling Tests

Yuill (78) has studied the hazards to life from the full scale burning of bedding and upholstery, showing that there is a risk of ignition from small flames or heat sources (e.g. cigarettes).

Only a few model tests have been reported in the literature, although considerable work and emphasis has been placed on the mathematical modelling of fires. Lee (66) has shown fire-spread test models of upholstered furniture can contribute significantly to the understanding of the fire behaviour of furniture, comparing favourably with data generated from cloth upholstered furniture burns. Other work has been reported on fires in fifth scale models of rigid polyurethane foams insulation (i.e. paralleling fires on board refrigeration ships), with reasonable results (79).
CHAPTER 6: RESEARCH OBJECTIVES AND MATERIALS
6.1 Aims of the Research

A considerable amount of work has been conducted on the full scale fire testing of domestic furnishing materials. Although this work is at its most meaningful level, it is expensive due to the amount of materials consumed, the number of men employed during test in monitoring fire parameters, and in terms of increased time per test when compared with conventional small scale tests.

The overall considerations indicated the need for a relevant programme, and as a result of discussions in the industry, the following outlined research programme was initiated:

(a) to design and construct a test chamber which could measure simultaneously a number of fire parameters (ie. temperatures developed during fire, smoke and toxic gases evolution), with facility to observe the fire in progress. Then to assess the experimental rig and the potential of the apparatus to scaled down real-life fires

(b) to carry out any necessary modifications to the rig from the preliminary findings

(c) evaluate the fire parameters of a number of composite materials used in furnishings, using the chamber and employing a number of varying tests to determine how suitable these were as possible standard methods

(d) determine fire properties of materials using standard small-scale tests and thermal analysis equipment.

The justification of scaling down should be shown by the results produced being similar to those found by the Inter-Company Urethane Panel tests.
6.2 Test Materials

In all the tests described below a range of typical domestic furnishing fabrics and fillers were used; they were supplied by Shell Research. The details of the materials are shown in Table 15 and 16 (see below).
## TABLE 15: Seat Fillers Supplied

<table>
<thead>
<tr>
<th>Filler Type Supplied</th>
<th>Abbreviation Used</th>
<th>Manufacturer</th>
<th>Density (kg/m³)</th>
<th>Chemistry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Fire Retarded Standard PU Foam</td>
<td>NFR</td>
<td>ICI</td>
<td>38</td>
<td>TDI/polyether (triol 3000 to 5500 mol wt; 0 to 45% primary OH; OHV = 40 to 50). Blown by Water/Freon 11. Catalysed by Sn salt/amines.</td>
</tr>
<tr>
<td>Fire Retarded PU Foam</td>
<td>FR</td>
<td>ICI</td>
<td>40</td>
<td>TDI/polyether with sufficient tri-(chloro propyl) phosphate to give self-extinguishing to ASTM 1692</td>
</tr>
<tr>
<td>High Resistance PU Foam</td>
<td>HR</td>
<td>Shell</td>
<td>32</td>
<td>TDI/MDI/Polyether. Blowing agent Freon 11/Water, amine catalysed. Triols to 4500 mol wt. 75%. Primary OH,OHV = 28 to 38. Triol used as crosslinker</td>
</tr>
<tr>
<td>Latex Foam (Pincore)</td>
<td>L</td>
<td>Hairlok Ltd</td>
<td>65</td>
<td>Natural rubber latex foam, without fire retardant</td>
</tr>
<tr>
<td>Rubberised Hair</td>
<td>RH</td>
<td>Hairlok Ltd</td>
<td>30</td>
<td>Horsehair matrix bonded with natural rubber latex</td>
</tr>
</tbody>
</table>

Notes: (1) The grades of material were chosen to have similar hardness, irrespective of density, since it is on this basis foams are chosen for furniture applications.  
(2) The fillers were supplied in 3000 cc blocks (ie. 7.5 x 20² cc). The non-flame retarded foam was also supplied as a 2.5 mm thick sheet.
## TABLE 16: Covering Fabrics Supplied

<table>
<thead>
<tr>
<th>Composition(W/W)</th>
<th>Abbreviation</th>
<th>Trade Name</th>
<th>Manufacturer</th>
<th>Colour</th>
<th>Weight (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Wool Fibre</td>
<td>W</td>
<td>Marksburg</td>
<td>Parterex</td>
<td>Blue</td>
<td>0.045</td>
</tr>
<tr>
<td>30% Cotton/70% Acrylic Fibres</td>
<td>C/A</td>
<td>Victor</td>
<td>John Lewis</td>
<td>Gold or Pale Green</td>
<td>0.039</td>
</tr>
<tr>
<td>50% Wool/50% Rayon Fibres</td>
<td>W/R</td>
<td>Torcross</td>
<td>Parterex</td>
<td>Beige</td>
<td>0.035</td>
</tr>
<tr>
<td>45% PU on 55% Cotton Scrim</td>
<td>PU</td>
<td>Storvic 220</td>
<td>Storey Bros</td>
<td>Beige</td>
<td>0.036</td>
</tr>
<tr>
<td>100% Plasticised PVC Sheet</td>
<td>PVC</td>
<td>Ambla</td>
<td>ICI</td>
<td>Beige</td>
<td>0.075</td>
</tr>
</tbody>
</table>

**Notes:**
(i) All fabrics were readily available in a well-known national chain store.

(ii) All had been chosen as representing (chemically) a large proportion of those used in domestic upholstery, according to information supplied by the Furniture Industries Research Association.
CHAPTER 7: PRELIMINARY DESIGN AND CONSTRUCTION OF TEST CHAMBER
FIG. 5: SCHEMATIC DIAGRAM OF CHAMBER
(Showing Relative Positions of Monitoring Equipment.)

Key:
A1/A2/A3: Gas Sampling Points
B1 to B6: Thermocouple Positions
C1/C2: Photometer Smoke Detection Pots (Entry and Exit Respectively)
FIG 6: FRONT ELEVATION OF ORIGINAL CONSTRUCTION OF TEST CHAMBER.
7.1 Original Design Concept

The test apparatus was to be considered as a simple chamber in which materials could be burnt in any manner of ways, and certain resulting fire parameters could then be determined. In this preliminary stage of design where a sample rig had to be quickly built as part of a feasibility study of a medium scale fire test, construction materials were selected as being effective and readily available. Types of material used in the construction anticipated the hostile environment that might arise during a fire (ie. materials were heat and chemical resistant). The early tests had to develop the basis of a fire testing technique, and to assess its viability in comparison with either large or small scale fire tests. Since these early tests were carried out burning typical domestic furnishing composites, the facility and tests were to be tailored towards this end. Even so, at this early stage, the chamber had to be designed with a view to possible reconstruction and variation of test in mind.

Figure 5 shows the basic concept of the preliminary design layout of the chamber. A metre cube was selected as a convenient size for the chamber, the volume being larger than most small scale fire test rigs. The apparatus would be capable of monitoring changes in temperature, smoke level, and also toxic gas levels. The observation of the fire was considered important, and a large window was inserted in the access door. A good fume extraction system was also designed as part of the apparatus.

7.2 Construction of the Chamber and Monitoring Equipment

7.2.1 The Chamber

Figure 6 shows the front external view of the chamber. The chamber was essentially a box of firebrick walls and floor, with a roof of $\frac{1}{4}$" asbestos board, screwed and cemented to the upper layer of firebricks.
The firebricks were bonded together using a fireclay cement, and the floor supported on angle iron pieces. The whole chamber was supported on two brick piers. To minimise leakage of fumes out into the laboratory, the internal surfaces of the chamber were coated with a thick slurry of fireclay on a support of chopped strand fibre glass mat; this was allowed to dry thoroughly before the chamber was used. The final interior dimensions were 100 x 92 x 92 cm$^3$, (ie. height, width and breadth respectively), giving a volume of 0.846 cubic metres. The observation door was in the centre of the front wall, and was a box constructed of stainless steel panels riveted together. Two square panels were removed and replaced by two "Pyrex" casserole dishes (10" square x 2" deep), to act as windows. These were sealed into position with silicone rubber and surrounded by glass wool. To aid cleaning of the observation panel, disposable "Melinex" film was taped over the back of the panel.

It was initially thought the air supply inside the chamber might not be sufficient to produce complete combustion of a test piece, therefore an airbrick (with eight 1cm diameter holes drilled through it) was placed centrally at the bottom of the front of the chamber. It was quickly discovered that burning polyurethane foam produced a large volume of smoke which escaped through these vents, and that calculations of fire loads showed the volume of air was sufficient to produce complete combustion, so the holes were sealed.

An exhaust outlet was inserted at the lower rear of a side wall. This metal vent was sealed by a neoprene rubber flap during test. The vent was connected to an extraction system by a silicone coated fabric pipe (7.5 cm diameter).
FIG 7: INTERIOR VIEW OF ORIGINAL CONSTRUCTION OF TEST CHAMBER.
A simple dyed water manometer was used to monitor atmospheric pressure change inside the chamber, with the manometer passing through the centre of a side wall.

All monitoring equipment was sealed or supported in position with fire clay.

7.2.2. Ignition System

The Inter-Company Urethane Panel tests had shown that most furnishing composites tested were self supporting once combustion had started. Therefore for these preliminary tests a simple gas flame was selected as ignition source. It was to be used to initiate ignition in a sample, and once the fire had taken hold the gas supply would be turned off.

The system consisted of a propane burner, the barrel of which passed vertically through the base of the chamber, while the air inlet was situated externally. The burner also had an extension sleeve of copper pipe fitted (1.5cm internal diameter), angled above the contact point at approximately 45° and flattened slightly at its upper end. The nozzle formed was 2cm long and 0.3cm wide (See Figure 13). So the gas outlet was centrally situated 18cm above the floor of the chamber, into which the burner was cemented, and supplied by a 21.5 lb "Calor" gas cylinder fitted with a regulator. The resulting flame was fan shaped and blue with a yellow tip in colour, showing incomplete combustion and suggesting a maximum flame temperature of below 1200°C.

Figure 7 shows the positioning of the burner.

Early tests revealed that on closing the chamber door, the burning gas was blown off the tip of the burner. This resulted from the velocity of
the propane gas flowing through the burner, being too great to maintain a fixed flame, when subjected to tiny draughts of air. It was found convenient to ignite the gas after the chamber door had been closed. A coiled high resistance wire (10cm in length), balanced on the nozzle of the burner was used for this purpose and was heated to orange heat by a 12 volt car battery to ignite the flame. Once alight the coil could be pulled away via its leads, through the airbrick vents.

### 7.2.3. Temperature Monitoring

It was decided to measure the temperature at several fixed positions within the chamber relative to the burn area, to give some indication of heat release during a fire. It was important that these points were fixed so that accurate comparisons could be made between tests.

In all, five thermocouples were supported in the following positions inside the chamber:

(a) centrally 60cm from the floor (reference TC 13)
(b) centrally 90cm from the floor (reference TC 11)
(c) centrally 10cm from the back wall, at 30cm from the floor (reference TC 5)
(d) centrally 10cm from the back wall, at 60cm from the floor (reference TC 3)
(e) centrally 10cm from the back wall, at 90cm from the floor (reference TC 1).

The thermocouples were constructed of chromel-alumel (for a good linear voltage-temperature relationship), threaded through protective sheaths and passing vertically up through the roof of the chamber. Wire traces strung across the interior of the chamber supported the thermocouples in position. Outside the chamber the thermocouples

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FIG. 8: POSITIONS OF THERMOCOUPLES IN TEST CHAMBER.
wires were protected by glass cloth sheathing made rigid with polyester resin. A sixth thermocouple was included, this was a flexible removable probe, which could be inserted into the test sample, to follow fire spread (reference TC 15).

The six thermocouples were relayed through a "Comark 1694" selector unit to a "Comark 1602" electronic thermometer for ease of temperature monitoring. The temperatures were monitored every 60 seconds, with a 10 seconds delay between each position. Figure 8 shows the position of the thermocouples.

7.2.4. Smoke Emission Monitoring

The essential of most smoke emission monitors is the photometric measurement of the attenuation of a light beam due to smoke build up. Due to the size of the chamber and the possibility of stratification of smoke during test, a system with a vertical light beam was selected.

Light from a filament of an electric light bulb was focussed by a double convex lens to give an approximately parallel beam. This passed up through the chamber to fall upon a photo-electric cell. To prevent stray light effecting the photocell, both it and the lamp were housed in copper tubing. To protect the optics from smoke, both tubes were covered by a flat glass plate sealed into position with epoxide resin. It was found that as the internal temperature of the chamber increased above the atmospheric dew point, water condensed on the cold lower protective glass window of the lamp set up. This was overcome by using a coiled resistance wire, one metre in length, sealed beneath the window, to heat it and the immediate surrounding air to approximately 60°C. The coil was supplied from 12 volt battery to give the required temperature.
FIG 9: ORIGINAL SMOKE DETECTION UNIT.
This circuit was modified to type 2, because transistor cut off when low light intensity reached, since base current too low.

The problem with type 1 overcome by putting 100K resistor in parallel with photocell output, and hence reducing gain in common emitter. This was further modified by removing output circuit and gain achieved by using the chart-recorder back off.
FIG 11: PHOTO-CELL ORP12 CALIBRATION CURVE.
FIG 12: ORIGINAL GAS SAMPLING APPARATUS.
The detailed structure of the apparatus is shown in Figure 9. The microscope bulb was driven by a 6.3 volt mains transformer for long life with the necessary light emission stability. The light beam fell on to a ORP 12 photo-electric cell in an electronic circuit driven by a 10 volt direct current stabilised source (ie. "Aplab" LVE 30/2 regulated direct current power supply). Before any tests were carried out, two modifications were made to the circuit, (these are shown along with reasons for change in Figure 10). The amplification circuit of the photo-electric cell was connected to a chart recorder (ie. "J.J." Chart recorder CR 100 set at 5mV/cm vertical response). The chart recorder was arbitrarily calibrated for 0 to 100% obscuration, which in turn was converted to neutral optical density (N.O.D.) This conversion was conducted using Kodak neutral optical density filters, the calibration curve of obscuration $V$ neutral optical density is shown in Figure 11.

7.2.5. Toxic Gas Sampling

The sampling of toxic gases was limited to the simplest and cheapest of apparatus and only single estimates of the concentrations of various gases could be determined on completion of the test.

Figure 12 schematically shows the apparatus used to sample the products from the fire. Three glass tubes (¾ inch internal diameter) passed through one side of the chamber, 71, 52, and 9 cm centrally down from its top. The tubes protruded 2 cm beyond the inner face of the chamber wall, allowing extension tubes to be fitted, for sampling from a variety of positions inside the chamber. Each sampling point could be isolated from the rest of the sampling circuit by means of a three-way valve. A simple glass wool plug inside each tube was used to filter out particulate matter. These tubes were connected to a master sampling tube (1.5 inches internal diameter), with its own two sampling points. A thick walled
polyethylene sampling bottle (9675cc total capacity) which could be isolated from the circuit by valves at either of its inlets, was used to collect gases for subsequent analysis (eg. isocyanate or hydrogen chloride). Details of TDI wet analysis is given in Appendix 4.

A "Rotameter" flowmeter was set well away from the chamber to prevent contamination, and as a means of estimating a constant positive flow (set at 1500cc/minute). A cold trap was used both to prevent water vapour reaching the vacuum pump (used to draw contaminated air from the chamber) and for sampling purposes.

7.3 Preliminary Evaluation of the Chamber

7.3.1 Initial Setting Up of the Chamber

The main requirement in the early work was to quickly assess the test potential of the rig as a "mid-scale" fire test facility. The materials available were domestic furnishing composites as described in Chapter 6.2. It was necessary in this work to devise a test method which burnt these materials in a manner similar to that found in full scale tests. The 1 cubic metre chamber (representing a 90m³ living room), required 3 litres of seat filling material (representing the 0.39m³ of furnishing filling of the RAPRA I test) and an equivalent surface area of 500 sq.cm. of fabric covering (representing an original 5.6 sq.m).

(i) Test Sample Frame

A simple design for a sample holder, which was quickly manufactured is shown in Figure 9. As the original samples were limited to the 7.5 x 20cm³ dimensions, the number of possible burning positions in relationship to the fixed burner was limited. Namely these were the "vertical" (ie. base dimensions: 7.5 x 20cm³)

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FIG 13: ORIGINAL GAS BURNER DESIGN.
or to the "horizontal" (ie. base dimensions 20 x 20cm²).

For the vertical sample test, the frame shown in Figure 9 was devised. This was constructed from chicken wire on five sides of the sample and a few degrees out of vertical to lessen the likelihood of the sample toppling out of the frame. The frame was fixed to the top of a standard chemistry tripod stand, which in turn stood on an aluminium bridge, to give the correct height for the sample above the burner. This aluminium bridge also prevented any droplets, oils etc. falling directly on to the absorbent fireclay floor. The horizontal sample was rested centrally on the tripod itself.

The precise positioning of the sample inside the chamber in relationship to the burner, and monitoring equipment is described later, at each stage of test variation.

(ii) Evaluation of the Burner and Ignition Burn Times:

At the design stage it was thought necessary to achieve a flame with the maximum flame temperature possible (ie. indicated by a blue flame untipped by yellow) with a combustion reaction approximately to:

\[ \text{C}_3\text{H}_8 + 5\text{O}_2 \rightarrow 4\text{H}_2\text{O} + 3\text{CO}_2 + \Delta H \]

and little or no carbon monoxide. The only available control on the flame type was the Bunsen air inlet valve, which was set to allow a maximum supply of air to flame, but whose flame was still tipped with yellow. Unfortunately, the following could not be altered:

(a) flame dimensions (ie. width and height)
(b) flame temperature
(c) gas flow

Figure 13 shows the appearance of the burner.

A number of uncovered non fire retarded foams were burnt with
different exposure times to the ignition flame or ignition burn times (IBT) (ie. 30, 60, 75 and 240 seconds), to establish if any resulting difference occurred in the time a self-supporting flame remained in the sample. The initial contact point of the flame was at the middle of the lowest front edge. Full resulting fire parameters were measured and results tabulated under reference A.1.1. in Appendix 1. From these tests a 60 seconds ignition burn times was selected.

(iii) Evaluation of Geometry of Burning:
A number of uncovered non flame retarded samples were burnt in different positions in relation to the ignition flame, to determine which produced the maximum levels of combustion and consumption of sample. Test samples were set up as follows:

(a) vertical specimens were burnt with the flame tip against the centre of the front lower edge (test reference number 1.1)

(b) horizontal specimens were burnt with the flame tip under the specimens playing against the centre of the base (reference 1.6) A bridge was used to raise the sample to the correct height from thermocouple 13

(c) vertical specimens were burnt with the flame tip playing at the centre of the base. A bridge was used again for positioning purposes.
Geometry as described in (c) was selected. Results are found in Appendix 1.1.

(iv) Sampling of Toxic Gases:
It was thought stratification of gases, and hence variations
in concentration inside the chamber might occur (ie. before complete diffusion occurred). Therefore while the tests described in the section immediately above were carried out, sampling at any of the three points or in combination was conducted. An extension tube was also fitted to the centre tube so that samples of gas could be taken from the centre of the chamber. The gas analysis figures indicated similarities of sampling at each point and in combination, within the error experienced for the Dräger tubes used. For example, in comparing three samples of non fire retarded foam under the same conditions of burn, and with 85% of each burnt away, the following figures resulted:

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Sampling Position</th>
<th>CO (ppm)</th>
<th>NOx (ppm)</th>
<th>HCN (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Top</td>
<td>400 - 500</td>
<td>200 - 300</td>
<td>5 - 10</td>
</tr>
<tr>
<td>1.1</td>
<td>Middle</td>
<td>400 - 500</td>
<td>200 - 300</td>
<td>5 - 10</td>
</tr>
<tr>
<td>1.1</td>
<td>Bottom</td>
<td>400 - 500</td>
<td>200 - 300</td>
<td>5 - 10</td>
</tr>
<tr>
<td>1.4</td>
<td>Middle</td>
<td>400 - 500</td>
<td>200 - 300</td>
<td>5 - 10</td>
</tr>
<tr>
<td>1.6</td>
<td>Middle</td>
<td>1000</td>
<td>200 - 300</td>
<td>15 - 20</td>
</tr>
</tbody>
</table>

For the rest of the experiments only the central tube was sampled from, the upper and lower tubes being closed off.

7.3.2. Preliminary Fire Testing

The standard test procedure for the preliminary fire testing is described in Appendix 5. Table 17 shows the combination of fillers and fabrics tested. Since materials were of a limited quantity at this stage, only a restricted number of combinations were burnt.
TABLE 17: Filler-Fabric Combinations Tested

<table>
<thead>
<tr>
<th>Fabric</th>
<th>NFR</th>
<th>FR</th>
<th>HR</th>
<th>L</th>
<th>RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wool</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cotton/acrylic</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wool/rayon</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PVC</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Uncovered</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Note: The number indicates the number of tests carried out for each combination and for the same set-up of test rig.

Scaling down the dimensions of filling and fabric (ie. in a volume to surface area ratio respectively) from the full scale originals, resulted in the surface area of the fabric being less than that required to completely cover the filling, and hence some of the filler was exposed. Thus the problem arose of how to produce a realistic comparison with the full scale tests, in producing realism while minimising the effect the exposed filling would have on an overall burn. Several variations in the wrapping of filling with fabric were possible, namely:

(a) Total coverage of the filling with fabric: but this gave a disproportionate amount of fabric in the combination (ie. approximately 1:1 by weight for most compositions)

(b) using the correct scale down ratio (ie. with 500cm² of fabric): this gave the foam only limited protection from the ignition flame. This arrangement was shown to be fairly unworkable, since flame would rapidly spread to the exposed surfaces of the filler, producing a burn similar to that for an uncovered filler.

(c) as in (b) covering the filling as far as possible, and covering the rest of the filling with a porous, close
**FIG 14: FABRIC TEMPLATES USED IN PRELIMINARY TESTS.**
knit and non-flammable material, which allowed heat transfer but not flame transfer.

The latter combination was selected as it was thought it most closely represented the real-life composition in fire situations. A grade of glass fibre cloth (ie. single layer chopped strand) was selected to meet the following requirements:

(a) thin enough to transmit heat, but act as a flame barrier (ie. the Davy effect shown by a miner's lamp in the presence of fire damp)
(b) negligible fire load
(c) readily draped to geometry of sample
(d) easily fixed to filler.

For these early burns cloth was cut to 20 x 25cm² (ie. 500 sq.cm), and in all tests the flame was in line with the warp of the fabric. The flame tip was initially in contact with the fabric in all tests.

Two types of wrapping of the fabric about the filling were examined:

(a) fabric covering the base of the filling and equally up each of the largest faces (ie. 8.75cm up each face)

or (b) fabric covering the complete front large face, the remainder covering part of the base.

Both these modes of wrapping are shown in Figure 14.

The second wrapping method was selected, since the flame was allowed to act more freely over a large surface of fabric before impinging on the glass cloth. The fabric and glass cloth were stapled to the filling with the minimum number of fixings; the glass cloth slightly overlapped the fabric.
Table 18 shows the references allocated to each test piece type, and results and relevant graphs are shown in Appendices 1.1. and 2.1. respectively.

TABLE 18: Key to Preliminary Test References

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Foam</th>
<th>Fabric</th>
<th>Ignition Time (sec)</th>
<th>Burn Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>NFR</td>
<td>-</td>
<td>60</td>
<td>Mid Bottom Edge of Front</td>
</tr>
<tr>
<td>1.2</td>
<td>NFR</td>
<td>-</td>
<td>75</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.3</td>
<td>NFR</td>
<td>-</td>
<td>240</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.4</td>
<td>NFR</td>
<td>-</td>
<td>60</td>
<td>Centrally under Base</td>
</tr>
<tr>
<td>1.5</td>
<td>NFR</td>
<td>-</td>
<td>70</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.6</td>
<td>NFR</td>
<td>-</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.7</td>
<td>FR</td>
<td>-</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.8</td>
<td>HR</td>
<td>-</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.9</td>
<td>L</td>
<td>-</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.10</td>
<td>RH</td>
<td>-</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.11</td>
<td>NFR</td>
<td>C/A</td>
<td>60</td>
<td>Centrally under Base</td>
</tr>
<tr>
<td>1.12</td>
<td>NFR</td>
<td>W</td>
<td>60</td>
<td>Centrally under Base</td>
</tr>
<tr>
<td>1.13</td>
<td>NFR</td>
<td>C/A</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.14</td>
<td>NFR</td>
<td>W/R</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.15</td>
<td>NFR</td>
<td>PU</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.16</td>
<td>NFR</td>
<td>PVC</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.17</td>
<td>FR</td>
<td>W</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.18</td>
<td>HR</td>
<td>W</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.19</td>
<td>L</td>
<td>W</td>
<td>60</td>
<td>&quot;</td>
</tr>
<tr>
<td>1.20</td>
<td>RH</td>
<td>W</td>
<td>60</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Notes: (a) All samples on top of tripod held vertically in frame except 1.6 which had 20^2 cm^2 face to base
(b) All fabrics covered, included glass cloth to cover remaining exposed surfaces (except 1.11)

7.4 Discussion of the Preliminary Test Results

7.4.1. Setting Up Tests

(i) Comparison of Ignition Burn Times

By increasing the ignition burn time, there was very little difference in the resulting fire parameters in both groups of ignition positions of vertical samples. Sample 1.3 fell from the holder, smothering its own flame, and effecting all other parameters.
In tests involving uncovered polyurethanes, the foam rapidly burnt away and out of the influence of the igniting flame, indicating all but a few seconds exposure was excessive. However, the composites burnt less rapidly and 60 seconds appeared to be a suitable maximum ignition burn time.

(ii) Comparison of Geometry of Burn

The uncovered non fire retarded foam was ignited at three different positions:

(a) Middle of the lower edge of the vertical face (ie. sample references 1.1, 1.2, 1.3), the base being 20 x 7.5cm²
(b) Centre of the base, being 20 x 7.5cm² (ie. references 1.4, 1.5)
(c) Centre of the base, being 20 x 20cm² (ie. reference 1.6)

The position detailed in (a) produced incomplete incineration of the foam, and relatively lower temperature profiles than those of position (b). Vertical flame spread was limited to the front vertical face for a significant part of the burn. With (b) spread occurred readily in both large vertical faces. Although not complete, weight losses for (b) samples were greater than those for (a) samples.

At the position detailed in (c) where flame spread rate was low, heat from the ignition source tended to pyrolyse the foam, rather than cause combustion. As a result smoke levels were higher, as were the toxic gas levels, although nitrogen oxides only reached levels immediately dangerous to life.

Note: Typical levels of toxic gases that will cause immediate danger to life are: nitrogen oxides 200 - 700 ppm (nitrogen dioxide specifically)
carbon monoxide  3000 - 5000 ppm
hydrogen cyanide  200 - 300 ppm
isocyanate  0.02 ppm (level at which there might be irreversible effect on human physiology).

The position detailed in (b) produced temperatures at thermocouple TC 13 greater than 400°C, and there was an indication of a rapid heat rise through the chamber. For position (a) temperatures were lower, and position (c) cannot be compared due to its morphology being different from that of either (a) or (b).

Geometry (b) was selected as producing the most rapid spread of fire, but it was observed that drops of oil from the decomposing foam could partially block the burner.

(iii) Comments on Experimental Preparation
(a) Temperature Monitoring
At thermocouple TC 13, the maximum temperature recorded could only be assumed to peak at 300 to 400°C after 50 to 70 seconds for test sample 1.5. This problem of non continuous monitoring prohibited precise maximum temperatures and times to these maximums to be accurately measured. The graphs plotted of time versus temperature do little to alleviate the problem (see Appendix 2, Graphs 1.1 onwards).

Heat flow through the chamber, generated from a sample in a type (b) burn, follows the order: thermocouple TC 13 11 3 5 1

(b) Smoke Monitoring
Smoke obscuration cannot be calculated in terms of specific optical density since irregular patterns of fire acted on the surface of the test piece (cf AMINCO smoke test with a standard 2.5 watt/cm³ heat flux falling on a \( \frac{215}{16} \) square surface). Early in the tests, the obscuration, \( 0 \), derived from

\[
0 = (100 - T)^\% 
\]

97
was determined, but it was found more convenient to convert to a neutral optical density (NOD) equivalent using calibration filters, especially for more meaningful results at higher smoke levels.

For samples reference 1.1 to 1.6, neutral optical density equivalent to 0.1 (equivalent to an obscuration of ~20%) times were less than 80 seconds for an obscuration of 50% times were less than 3 minutes.

(c) Toxic Gas Sampling

All gas sampling was conducted at least four minutes after a flaming ceased. Gas samples taken separately from the upper, middle, lower, middle with an extension tube, or the first three in combination, indicated gas stratification was minimal or non-existent, the gases mixing throughout the chamber to a uniform composition very soon after the fire had stopped.

In these tests TDI was not detected by wet analysis. Infra-red analysis revealed carbon dioxide present possibly in large concentrations for all tests. Oxygen levels also measured by a tediously long Dräger test showed that depletion was zero, at the end of a burn. This was surprising since partial pressure occurred during test, and carbon monoxide and dioxide gases were present. It was most possible that air leaked in to the chamber around the door re-establishing normal atmospheric pressure and oxygen levels, between the burn ending and analysis commencing.

7.4.2. Preliminary Fire Testing: Comparison of Uncovered Foam

(i) Polyurethane Foams

Non-fire retarded foam produced the greatest quantity of heat (estimated from it developing the highest temperatures over the longest period), and also remained self-burning for the longest period of all the polyurethanes. The fire retarded foam had the lowest temperature.
FIG. 15: BURN PATTERNS RESULTING FROM GAS-FLAME IGNITION ON UNCOVERED P.U.S.
profiles of all the fillings evaluated.

Both high resilience and non-fire retarded foams generated relatively low levels of carbon monoxide (400-500ppm) and hydrogen cyanide (5-10ppm), but nitrogen oxides were at the "dangerous for short exposure concentration" (150-250ppm). The levels of gas produced by fire retarded foam varied between samples, but showed dependence on the weight of foam burnt. It has been extrapolated from the results if polyurethanes were burnt completely in this mode of geometry, dangerous for short exposure concentrations of nitrogen oxides and probably carbon monoxides would be present. Considering the relative toxic gas levels of the three polyurethanes, the decreasing order of toxicity was

FR HR NFR

relating to the reluctance of the foam to combust. One sample of high resilience foam did produce 0.02 ppm of TDI by Dräger analysis, well below values estimated from other laboratory work but enough to cause concern for people continually exposed to foam fires.

Fire retarded foam properties had an effect on smoke emission, producing a neutral optical density $\equiv 2$ while the other polyurethanes were below neutral optical density equivalent to 1.6.

The Figure 15 illustrates typical burn patterns of the polyurethanes.

There is every indication that fire is mainly concentrated at the point where ignition starts, and lessens further away from this area. Spread moves up over the surface of the sample to the top of the specimen and then in to the bulk of foam nearest the ignition point. The presence of chars or viscous oils soaking into the unburnt foam, particularly in the fire retarded and high resilience foams, limited
the spread to primarily the surface of the sample. This suggested
the burner needed to be redesigned at a later stage of the work,
so ignition could be achieved over a wider area, and possibly boost
combustion heat to volatilise the oil and eliminate this effect.
The oil had been shown by infra-red analysis to be mostly polycyl,
and the flash point of most commercial polyether polyols is over
300°C. The oil was found in large quantities under the sample holder,
well away from the fire centre, and in the unburnt foam, giving rise
to low values of weight loss.
(ii) Latex
From its temperature graphs (see Appendix 2.1), latex was thought to
have released the greatest quantity of heat into the chamber, in
maintaining chamber temperature higher than for any other filler. The
relatively greater weight of foam burnt contributed to the extra fire
load.

In losing one third of its original weight, latex produced considerable
quantities of carbon monoxide (well above the dangerous for short
exposure concentration). As might be expected hydrogen cyanide levels
were very low. Latex produced the most rapid and thickest smoke for all
of the five fillers. Its maximum rate of smoke production was also
many times greater.

Its foam structure readily collapsed on burning to a crumpled, hard
semi-rigid charred lump, which had a very nauseating odour of burnt
rubber.

(iii) Rubberised Hair
Rubberised hair burnt with the earlier heat build-up, thermocouple 13
indicating 400°C in less than 50 seconds. The spread of flame through
its width was far more rapid than the other fillers, which could have been expected from its open network (ie. excess air and minimal material to burn through). This also contributed to the fact that, as soon as the maximum temperature was reached, cooling occurred more rapidly than for any other filler.

Rubberised hair produced dangerous for short exposure concentrations of carbon monoxide, hydrogen cyanide and nitrogen oxides in its near-complete and fast combustion. It also only left an ash.

From observations of the burn, it was considered the most dangerous of the uncovered fillers for flame spread.

(iv) General Comments

The fillers may be ordered in descending value of hazard as follows:

- **Fire Spread:** RH L = NFR HR FR
- **Temperature Maximum:** NFR RH = L = HR FR
- **Toxic Gases:** RH L FR HR NFR
- **Smoke Evolution:** L RH FR HR NFR

Comment must be made if combustion had been complete for all the fillers, there would be some adjustment to these orders.

7.4.3. Preliminary Fire Testing : Comparison of Covered Non-Fire Retarded Foam Composites

Sample 1.11 (ie. Cotton acrylic composite without glass cloth) burnt quickly since flame spread passed beyond the cotton-acrylic and on to the exposed non fire retarded foam which became the main contributor to the fire. Hence the effect of cotton-acrylic on non fire retarded foam was not fully established, and hence glass cloth protection was selected.
(i) Heat Release

The temperature graphs drawn differentiate between the fabrics and the way they contribute to heat (and hence temperature) build up. The decreasing order in which temperature rise occurred at thermocouple 13 was shown to be:

CA W PU WR = PVC

(ii) Smoke Emission

In comparison to the uncovered non fire retarded foam, in fabric covering the foam smoke evolution was increased. It appeared that in the early stages of fire, the following occurred:

(a) fire occurred in the fabric, either charring or slowly melting it (ie. the woven 'thermoset' or thermoplastic fabrics respectively)

(b) in most cases pyrolysis rather than combustion occurred in the foam, and smoke plus relatively large concentrations of gases, were formed in preference to flame

(c) as the char broke away or plastic melted away, the exposed foam ignited with observable flame. However the fire spread was mainly restricted to the foam, since the remaining charred or unmelted fabric or glass cloth impeded progress

(d) foam pyrolysis still continued supplying flammable fuel to the fire, producing fire spread independent on the fire properties of the particular fabric. The characteristics of the first few minutes of burn were very dependent on the fabric

(e) the foam slowly descended, usually to the lower parts of the specimen holder, the fire fortunately acting through the remaining fabric rather than the glass cloth which stayed in the upper framework.
On the basis of time to maximum obscuration, (neutral optical density $\approx 2$ in all cases) the decreasing order of smoke producers was as follows:

\[ \text{C/A PVC W PU W/R} \]

but in terms of maximum rate of smoke production the decreasing order was:

\[ \text{PU C/A PVC W W/R} \]

(iii) Toxic Gas Emission

In all cases at least 50% of the composite weight was lost. In comparison to the uncovered non fire retarded polyurethane, carbon monoxide and hydrogen cyanide had reached dangerous for short concentrations while nitrogen oxides remained steady, and polyurethane fabric covered foam produced the greatest levels of carbon monoxide ($>3000\text{ppm}$).

In all cases the fabrics burnt to near completion, while the foam remained partially consumed (usually at a weight loss less than that for non fire retarded foam alone). It is fair to suggest that the fabrics increased pyrolysis of the foam with consequent increase of carbon monoxide and hydrogen cyanide. The covered foam, especially with polyurethane fabric, produced a yellow smoke, but isocyanate was not detected.

(iv) General Comments

With all the fabrics tested, once char had occurred (ie. in wool-rayon, cotton-acrylic and wool) the ignition source was only acting on a limited area of the specimen.

The decreasing order of flammability for covered non-fire retarded foam was as follows: C/A W PU PVC W/R, a similar order was followed for decreasing order of fire damage (on weight basis).
7.4.4. Preliminary Fire Testing: The Covering of Filler with Wool

Thermocouple 13 indicated that latex produced the greatest heat release, and fire retarded foam the lowest. In order of decreasing heat release (from both TC 13 and TC 11): L NR NFR HR FR

Smoke levels of neutral optical density equivalent $>2$ were all produced within 130 seconds. Wool increased carbon monoxide levels to dangerous for short exposure concentration for all the polyurethanes, while for latex and rubberised hair, carbon monoxide levels decreased while still at dangerous for short exposure concentrations. Hydrogen cyanide concentrations increased for all the fillers, suggesting a hydrogen cyanide contribution from the wool itself. Nitrogen oxides level remained steady or decreased, suggesting the wool, in perhaps promoting pyrolysis, acted to increase hydrogen cyanide levels at the expense of the nitrogen oxides.

In all cases wool initially formed an intumescent char, but by the completion of the burn, the char had broken away. This particular wool fibre appeared suitable to act as a heat source, to maintain the fillers above their ignition temperatures.

In general these covering fabrics have been shown to act as follows:

(a) initially as a flame barrier to the filler, which permitted heat to be transmitted to the filler promoting pyrolysis

(b) supporting flame, until it can burn through the fabric and be supported in the filler

(c) maintaining the surface of the filler at an elevated temperature.

All the covered polyurethane foams burnt producing an oily residue.
7.4.5. Comparison of Preliminary Tests with Inter-Company Urethane Panel Full Scale Work

At the time of completion of the preliminary tests very little information was available from the Inter-Company Urethane Panel on their RAPRA I to III tests. As a result only general comparisons could be made with RAPRA I burn. However, more recently data as shown in Table 14 (Page 62) has been made available. Effects of wrapping filler with fabric is shown in Table 19 (a) and (b):

**TABLE 19(a) : Effects of Wrapping Fillers with Fabric**

<table>
<thead>
<tr>
<th>Composite</th>
<th>Burn Time</th>
<th>Weight Loss</th>
<th>Max: Temp</th>
<th>Time to 50% Obscuration of Smoke</th>
<th>CO (max)</th>
<th>NO(_x) (max)</th>
<th>HCN (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFR</td>
<td>*</td>
<td>*</td>
<td>**</td>
<td>*</td>
<td>***</td>
<td>*</td>
<td>***</td>
</tr>
<tr>
<td>FR</td>
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<td>HR</td>
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<tr>
<td>RH</td>
<td>***</td>
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<td>*</td>
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<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>NFR-W</td>
<td>**</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>NFR-C/A</td>
<td>*</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td>NFR-W/R</td>
<td>*</td>
<td>**</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td>NFR-PU</td>
<td>**</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td>NFR-PVC</td>
<td>**</td>
<td>**</td>
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<td>**</td>
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<td>*</td>
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<tr>
<td>FR-W</td>
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<td>*</td>
</tr>
<tr>
<td>HR-W</td>
<td>*</td>
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<td>***</td>
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<tr>
<td>L-W</td>
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<td>*</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>RH-W</td>
<td>**</td>
<td>*</td>
<td>**</td>
<td>*</td>
<td>*</td>
<td>**</td>
<td>**</td>
</tr>
</tbody>
</table>

Key:

* \(>240\text{sec}\) 60-100\% 600°C \(<90\text{sec}\) 1500ppm \(>100\text{ppm}\) \(>50ppm\)

** 120 - 33-66\% 200-600°C 90-180 500 - 80 - 50 -

*** \(<120\text{sec}\) 0-33\% \(<200°C\) \(>180\text{sec}\) \(<500ppm\) \(<80ppm\) \(<50ppm\)

* levels to produce death in less than one hour.
<table>
<thead>
<tr>
<th></th>
<th>Toxic Gas</th>
<th>Smoke</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO</td>
<td>HCN</td>
</tr>
<tr>
<td>NFR</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>FR</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>HR</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>L</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>RH</td>
<td>↓</td>
<td>↑</td>
</tr>
</tbody>
</table>

Key:
↑ increase
↓ decrease
← no change

Similarities were found especially in terms of temperature rise, which occurred in the early stages of a fire, although maximums were slightly lower. Fire parameters which were dependent on the latter stages of the burn differed slightly. Orders of smoke evolution were similar, but quantitative values were not available for either type of test. Toxic gas figures were similar for uncovered fillings, but the full scale composites produced relatively higher values, suggesting the mode of covering used might be producing the differences. It must be pointed out that most test pieces did not burn to completion (the vast majority did in the Inter-Company Urethane Panel tests), again suggesting that the fire parameters for all samples should have been higher.

In conclusion it was shown that these preliminary experiments were of value and that the rig had some potential as a small scale test facility in parallelling results for certain composites (ie. qualitative rather than quantitative tester). It was thought that with suitable design modifications, to tighten up positioning problems and to improve the
monitoring of fire parameters and followed by a fuller examination of test method variations, a suitable laboratory scale facility might be produced. Further experiments may eliminate any difference or at least explain some reasons for them.

It was suspected before starting any of these tests that the volume of air in the chamber would not support a complete combustion. However, experimental observations showed several burns reached near completion, and any incompleteness was thought more likely due to an ignition or a sample geometry problem, which could be established in later tests. If, in fact, these are not the reasons for incompleteness and insufficient air was to blame, at least the burn may be paralleled with sealed room situations.
CHAPTER 8: RECONSTRUCTION OF CHAMBER
8.1 Design Concept of Reconstructed Chamber

The preliminary work on domestic furnishings using the test chamber showed many shortcomings; however, it also showed the chamber had potential as a "mid-scale" fire test apparatus. The early work revealed faults in design and test ideas, and changes were made in light of this knowledge.

While maintaining the concept of a simple structure, it was decided the rig must give greater flexibility in type and range of test. It was thought this should be achieved in allowing any form of burn, at any position inside the chamber, of any sample geometry and with any ignition source, to be carried out while the fire parameters could be measured at fixed positions inside the chamber.

It was thought the monitoring should cover the maximum number of parameters possible, and as many of these should be measured continuously during test.

8.2 Construction of the Chamber and Monitoring Equipment

8.2.1. The Chamber

In the haste to complete the chamber in the preliminary work, constructional problems were solved as simply as possible, but not always with complete satisfaction. Therefore at this stage, the fabric and nature of the chamber underwent some major alterations.

(i) The Roof

The roof of the original chamber was of \( \frac{1}{4} \)" thick asbestos board, which was too flexible, and permitted heat to be transferred to the monitoring equipment resting on it. These problems particularly affected the smoke
FIG 16: SCHEMATIC DIAGRAM OF CHAMBER, SHOWING ROOFING SUB-STRUCTURE.
detection apparatus which really needed a steady base to produce a constant light beam. In addition there was poor bonding between the asbestos and the fireclay allowing smoke to leak to the outside.

The roof was reconstructed from fire bricks bonded by standard builders' cement supported by angle iron frames screwed to the top of the side wall (see Figure 16). The builders' cement was selected for its superior bonding properties over that of fire clay, and after 200 burns appeared unaffected by heat or corrosive fumes. As the roof top was uneven, the areas where the various monitoring services were to be rested, were levelled using cement.

(ii) The Door
Bad leakage of smoke and fumes from around the observation door occurred at most burns, even with the door locking-bar in position. It was both a result of a poor fit of the door in its frame, and the breakdown of the fireclay seal around the door, as it was continually opened and closed. The filling of voids about the frame, and repointing the bricks in the vicinity of the door with a fireclay-cement mix minimised the latter. The effect of the former was lessened by specially preparing neoprene foam strips (1" x 8") and sticking these around the edge of the rear of the door. Additional sealing of the door itself was facilitated by coating all joints, overlaps and rivets with fire-retarded polyester resin thickened with silica flour.

(iii) Interior Walls
The problems of the breakdown of the fireclay interior wall facing when subjected to heat over a period of time, the possibility of gas adsorption on to the fireclay and the difficulty of cleaning the wall thoroughly, were made apparent during the preliminary testing. It was thought a sealant material might overcome these problems, but it would have to also meet the following requirements:

(a) be a liquid material initially, which could be painted
directly on to the existing fireclay faces and on to the brick ceiling (formed by the roof)

(b) low adsorptive characteristics (a surface coating would have a lower adsorption than fireclay, being more coherent, having a lower surface area and probably a less active surface

(c) a material which readily bonded to fireclay, brick and any other materials (eg. steelwork) likely to be fixed inside the chamber

(d) excellent mild solvent resistance (ie. to those used to clean the chamber eg. industrial methylated spirits),

(e) high temperature resistance to corrosive gases (eg. hydrogen chloride), that could be released during a fire

(f) heat and fire resistance

(g) coloured black, or could be readily pigmented black, to give the chamber an interior colour, which would most likely remain constant whether in a clean or dirty state, and minimise heat loss and reflection variations during test. (Certain tests demand the test apparatus be its original interior colour at the beginning of each test, eg. AMINCO - NBS Smoke Detector, and it is green which makes for time consuming cleaning between each test!).

In addition all the properties had to last with long service of the chamber.

Several materials suggested themselves in meeting these requirements, including stoveable paints (eg. epoxide resin based paints) heat resistant unsaturated polyester resins and certain silicone rubbers. The stoveable paint regrettably had to be rejected since the chamber
could not be maintained at an elevated temperature to cure any paint system. Eventually two polymers were selected:

(a) "Crystic" 199, a heat resistant grade of polyester resin (ex Scott Bader)

(b) "Sylgard" 170 A & B, a heat resistant grade of silicone rubber containing an external phosphorous/bromide based fire-retardent (ex Dow Corning).

These polymers were subjected to some simple tests:

(a) application to possible substrates in the uncured state

(b) cure on these substrates

(c) short term heat and fire resistance.

Both could be readily painted on to a fireclay or brick surface, and if necessary be thickened with silica flour. The silicone bonded well to both surfaces, but polyester only bonded to the fireclay. The low viscosity of the "Sylgard" permitted excellent wetting out of the fireclay to a depth of some millimetres, thus reinforcing the clay and sealing large cracks, but several coats of silicone had to be applied to give complete coverage. In comparison with the polyester, silicone cured very slowly, particularly in thin sections where a tack-free state was reached after five days. Often cure had to be promoted by heating for several hours with an industrial hot air blower.

A simple fire test was devised to determine fire (and heat) resistance of the surface coating. A brick, with and without a layer of fireclay, was painted with the polymer, and allowed to cure at room temperature for at least seven days. Then a Bunsen burner flame (at least 1200°C maximum flame temperature) was applied directly to the coating. The polyester readily ignited with a luminous flame within a few seconds.
FIG 17: RELATIVE POSITIONING OF EQUIPMENT
of this harsh treatment, but the silicone with at least a minute of heating had only slightly lightened in colour. The silicone was otherwise unaffected, and was therefore selected to coat the interior surfaces of the chamber.

The "Sylgard" 170 was naturally black, due to the colour of the fire retardent present and was relatively low in viscosity giving rise to self-levelling properties. The walls, floor and ceiling were painted with a priming coat of the silicone, which was allowed to soak into the fireclay and partially cure, before the next coat was applied. Four additional coats were used to give a final glossy appearance.

(iv) Interior Illumination
To improve visibility inside the chamber, a 60 watt electric light was fixed to the back wall, encased in a "Pyrex" cover sealed into position by silicone coated fireclay. As the lamp produced some heat and so the temperature inside the chamber tended to increase, it was kept alight for the minimum of time. Figure 16 shows its approximate position in the chamber.

(v) Sample Holder Anchorage
In the preliminary tests the sample holder was not secured in position during the burn, giving rise to possible test variations. A simple frame for anchoring the sample holder was constructed from 1/4" iron angle frame (25cm x 25cm overall dimensions), and cemented centrally in to the base of the chamber. (See Figure 17). Most sample holders could now be bolted onto this anchorage to ensure rigidity and consistency in positioning the sample.

As an additional safeguard against escaping fumes, a large galvanised steel fumehood was placed over the whole of the chamber and monitoring
FIG 18: PROPANE-AIR MIXING UNIT.
FIG 19: FUEL GAS MIXING UNIT.
8.2.2 Ignition Fuel Supply

In the original structure, the ignition system had proved cumbersome and had very limited use. To overcome this, it was decided to have a unit in which the burner was not plumbed into the supply lines. This was achieved by having a gas line fed in beneath the surface of the floor, and coming up a few centimetres above the middle of it, the end of the piping being tapped with a screw thread. The pipe could be either capped with a closure nut when not in use, or alternatively have a number of burner designs screwed on to it. When the supply of gas was not required, there was no intrusion of unrequired pipes into the area of burn.

It was also thought necessary to introduce a controlled supply for a gas ignition system in the following way:

(a) fairly accurate metering and thorough mixing of the gas with air

(b) controlled flow of the gas and air, separately and mixed

(c) controlled flame heights.

Figure 18 shows the schematic arrangement selected. The gases passed through valve operated flowmeters and non-return valves to a "fuel mixer". This was a series of baffle plates to aid gas mixing and is shown in Figure 19. The mixed gases then passed onto the chamber via the burner. The gas mixing unit was kept at some distance from the chamber to minimise fire risk, but as a result produced a delay of some 30 seconds for an ignitable gas to reach the burners (i.e. overall length of pipe was 4 metres of $\frac{3}{8}$ inch internal diameter).
For the series of gas flame ignition tests described in Chapter 9, a propane-air fuel was selected, but the mixing unit was designed to allow any combination of gases to be used. For this propane-air fuel a number of maximum flame temperature/gas compositions and flow rate checks were made and are described in Appendix 8.

8.2.3 Temperature Monitoring

The original set-up for temperature monitoring proved fairly reliable, but the non-continuous recording of temperatures proved a major problem. Using a temperature display, reliant on manual switching (i.e. the "Comark" 1694 selector), and which then required the operator to record the data from the 5 or 6 thermocouples (each temperature recorded every 10 seconds), produced a severe restriction in both the recording of enough representative values of temperature and the full observation of a burn. The graphs drawn from the data (see Appendix 2.1.) show large gaps of information often as not where maximum temperatures were expected.

Therefore the temperature monitoring equipment was reconstructed, to permit continuous reading of at least six channels of thermocouple. A "Solatron" data logger punching values of millivoltage equivalents of degree centigrade on to tape from a "Data Dynamics" 110 Punch, were used to this end.

With the reconstruction of the burner unit, samples could now be burnt closer to the floor of the chamber, and so a sixth fixed thermocouple was included. This was placed in position immediately above the burn area, and it was expected this thermocouple would act as a parallel to the "temperature at ceiling" thermocouples.
FIG 20: CALIBRATION OF CHROMEL-ALUMEL THERMOCOUPLE.
used in the full scale work. Figure 8 (page 80) shows the positions of all the six fixed thermocouples, although a "flexible" thermocouple is not shown, it was occasionally used; the numbering is also shown.

(i) The Thermocouple Siting

All the thermocouples were held in place by wire supports strung taut across the width of the chamber. These supports were connected to tensioners which passed through the side walls of the chamber and then by adjusting these bolts the thermocouples could be adjusted into the desired positions. Since the thermocouples were subjected to unintentional movement with the increased activity inside the chamber, the ceramic sheathing began to break up and these thermocouples were replaced by steel sheathed chromel-alumel thermocouples. Each was welded to a cold junction and to the data-log lines in series, and each of the cold junctions was glued into position equally spaced around the circumference of a 2.5 inches diameter polystyrene disc. The complete cold junction could be readily dropped into a litre vacuum flask containing ice/water. All the thermocouple lines were fed up through two steel conduit pipes passing through the roof of the chamber, sealed with a silicone putty.

Figure 20 shows the conversion of millivoltage to temperature (80). The chromel-alumel thermocouple shows an approximate linear fit up to 900°C with a maximum deviation from a true fit at 400°C of about 7°C. Due to data processing problems it was found easier to plot millivoltage against time graphically then convert the millivoltage scale to degree centigrade than converting the data using a computer.

8.2.4 Smoke Emission Monitoring

The original smoke monitoring system was extremely simple in design, and was prone to fluctuations of light output, (and hence steady
FIG 21: SCHEMATIC DIAGRAMS OF OPTICAL SET-UP.

A). PRELIMINARY UNIT.

B). UNIT ORIGINALLY CONSIDERED WITH FEEDBACK CIRCUIT.
photocell response). This stemmed from the filament of the lamp gradually decaying (possibly due to carbonisation), mains voltage fluctuation and roof instability. The poor stability of the original system resulted in considerable base-line drift over a single test (which lasted 20 minutes or more).

Therefore it was decided to totally redesign and construct the smoke detection apparatus, to iron out these problems or at least minimise them. To ensure that a standard level of light output be maintained throughout the test, it was felt necessary to include an electro-optical feedback system into the apparatus, along with improved voltage stabilisation for the lamp and photocell circuits.

(i) Optics

Figure 21 shows the three optical circuits used in the smoke detector set up. The preliminary system as described in Chapter 7.2.4. and Figure 9, is redrawn in Figure 21(a).

The first construction with a feedback unit (see Figure 21(b)) consisted of a long life mercury-halide lamp (type MBF/u ES 80W), which when inserted into the system proved to be a fluorescent bulb which was not capable of producing a coherent point light source. The bulb was replaced by a multi-filament microscope bulb (650 watt/240 volt run at 100 volts), which had a relatively short life. The light was focussed to parallel beams by two bi-convex lenses, so that a beam fell on to a reference phototransistor (the detector of the feedback unit), and the other beam passed through a 0.9 inch diameter slit, through a calibration disc, and then through the chamber to be finally focussed on to the sampling photocell. The
FIG 21C: PRESENT USED UNIT.
sampling photocell was to monitor smoke build-up and produce a millivoltage display on a chart recorder. A calibration disc stripped out of a "Hilger-Watts" atomic absorption meter was intended for the calibration of the sampling photocell (in neutral optical density) prior to each run. This system had the following associated problems:

(a) the calibration unit was difficult to build into the system and also badly reduced the diameter of the light beam produced by the optics

(b) the multi-filament bulb had too short a filament life and did not provide enough light since only one filament could be focussed on the photocells in the optical unit

(c) the optics were too simple, thus not allowing fine control of focussing

(d) the focussing lens immediately above the sample photocell, in concentrating the unattenuated beam swamped the sampling photocell causing it to lose most of its sensitivity and some of its response.

Thus the system shown in Figure 21(c) was developed. The light source selected was a single filament lamp (12 volts direct current driven by a stabilised alternating current power source, transformed to 12 volts direct current). Here the light passed through two bi-convex lenses, one to give a parallel reference falling directly on to the photodetector, the other giving a parallel sample beam. This passed through a 0.9 inch diameter slit, to minimise light scatter, on to a 40 thousandth of an inch diameter hole to improve focussing with a point source of light. The beam was then again condensed to a parallel beam via a second bi-convex lens and 0.9 inch diameter slit, and moved on to a front-silvered plain mirror on a swivel
bracket. Here the beam was turned through 90° down through the chamber to eventually fall on to the sample photo-Darlington amplifier. This amplifier was a self-contained amplifier/detector in a chip form, which simplified the electronic circuitry. A plain "Wratten" 106 filter (ex Kodak) was inserted into the sample beam set up to ensure the photocell response was as close to that of the human eye as possible, by reducing the infra-red response. The optical response of the "Wratten" 106 filter is shown in Figure 24, along with the response of the Darlington amplifier and that of the human eye. Where necessary the optics were set up on a rack and pinion track to allow fine positional changes to be made.

The fine adjustment for focussing the light beams was as follows:

(a) the lamp was turned on to a light intensity that did not cause swamping of either of the photo-detectors, and focussing lenses were set at convenient distances from it. The 0.9 inch diameter slits were permanently fixed to the base of the lens holders.

(b) the reference photo-detector at approximately the focal length (of its lens) from the lens was finely adjusted to give maximum response on the recorder.

(c) the pinhole screen was adjusted until a clear image of the filament fell on to it. It was found that the centre of the filament was brightest and the optics were adjusted to produce the image at this point

(d) the refocussing lens was adjusted until a clear image of the filament was produced at infinity (in practice at a distance of at least 4 metres), by a parallel beam

(e) the optical bench was placed in position on the roof of the chamber so that a parallel beam turned through 90° could pass vertically down through the chamber to form a
FIG 22: SCALE DRAWING OF SMOKE-DETECTION APPARATUS
FIG 23A: A.C. CIRCUIT FOR STABILISED LIGHT SOURCE.

Key:
- TR1/TR2 = MPS 6516 transistor
- TR3 = MPS 300
- T1 = Pulse Transformer
- R4 may be used to fire T1

This circuit takes in 50 Hz mains AC and converts it to phase angle current

which response to light output change, and puts it back to normal.
circular image on and around the sample detector. The fine adjustment of the beam location was carried out by rotation of the mirror.

(f) The "Wratten" filter was positioned, and any final adjustment of the mirror made. It was discovered that the beam was multi-coloured and maximum response was produced when green-yellow light fell on the photocell.

(g) Fine tuning of the optics was achieved by observing the response to light falling on the sample detector as recorded. The fine tuning (i.e., adjustment of all optical parts, if necessary) was made to give maximum response. The chart recorder was only used for initial calibration and setting up purposes. During these tests, smoke build up was recorded on the data logger, and the millivoltages recorded were later converted to neutral optical density equivalents.

The detailed optical set up used is shown in Figure 22. The upper optical housing was constructed and fixed on to a triangular optics bench which was screwed to a base of steel and a heat barrier of asbestos board cemented to the roof of the chamber. This construction was selected for its rigidity and minimum heat transfer from the chamber.

(ii) Electronics

The first circuit used having feedback is shown in Figure 23(a). This was an alternating current circuit (to drive the lamp) and consisted of a triac which was fixed by a pulse generator. The pulse repetition rate of the generator could be adjusted by the rate at which the capacitor charged up through a transistor network. The light level of the lamp was altered by the resistance R6. The reference phototransistor monitored the light level of the lamp, and if the light level increased, the transistor conducted more, which in turn
FIG. 23B: D.C. CIRCUIT FOR STABILISED LIGHT SOURCE & FEEDBACK UNIT.
decreased the rate of charge on the capacitor. This delayed the pulse on the unijunctional transistor firing the triac later and had the effect of reducing the voltage. If the light level decreased the opposite effect happened. The circuit was replaced by that shown in Figure 23(b) since:

(a) the lamp has associated problems (see above)
(b) the circuit could detect the A.C. wave form being chopped in operation, being very sensitive and was continuously compensating with unwanted light adjustment.

Figure 23(b) shows the present circuit consisting of a series voltage regulator and an optical feedback network. The series regulator provided a stabilised voltage to the feedback sections, and this was achieved with a Zener diode which gave a constant voltage across it. This voltage was fed into the base of the BC 107 and in turn into the base of the 2N 3055. This transistor arrangement is known as a Darlington pair. The overall gain of it was the multiple of the gains of the two transistors (i.e. BC 107's x 2N 3055's). Thus a greater current could be supplied from the circuit. The feedback network consisted of an operational amplifier in the differential mode with a Darlington amplifier to increase the output current of the circuit. The lamp was placed in the emitter of the power transistor (i.e. known as an emitter follower, where the voltage of the emitter follows the voltage on the base). The operation of the circuit was as follows:

(a) a phototransistor was placed near the lamp to monitor its output
(b) the 5kΩ pot was adjusted until the required light level was reached
The Photo Darlington Amplifier is used as the sample photodetector, having been found to be the most sensitive photodetector having a gain of ~2000. The base circuit is left open. Light impinging on the base increases leakage current to transistor feed to the next transistor. This amplifies that current by hfe (i.e. the current gain of transistor), allowing more current to flow through the load transistor. The voltage is detected across the transistor (i.e. across collector and emitter).

V = \text{amount of light falling on the base.}

**FIG 23C:** PHOTO-DARLINGTON AMPLIFICATION CIRCUIT.
FIG 24: COMPARISON OF OPTICAL RESPONSES OF AN AVERAGE HUMAN EYE, PHOTO-DARLINGTON AMPLIFIER & WRATTEN 106 FILTER.

Key:
- Response of human eye in feeble light (A)
- Response of human eye in bright light (B)
- Response of photo-Darlington amplifier (C)
- Response at transmission through 106 Filter (derived from work on Unimax SP200)
- Response of protective glass windows (derived from work on Unimax SP200)

References:
B. Mepore Laboratories:
2M5777 Thru 2M5778 (LS 2614 A1)
FIG 25: CIRCUIT USED TO DRIVE SMOKE DETECTOR'S WINDOW HEATERS.
(c) the voltage on the output = \[(\text{Voltage} + \text{Input}) - \\
(\text{Voltage} - \text{Input})\] x Gain.

Thus if the light level of the lamp increased, the phototransistor would have conducted more and had the effect of reducing the voltage. This would have had the effect of reducing the output voltage and decreasing the light level. If the light level decreased then the output voltage would have increased by a similar action. The sensitivity could be adjusted by changing the gain of the amplifier.

Figure 23(c) shows the photo-Darlington amplifier with associated circuit used in the smoke sampling photodetector.

(iii) Protective Housing

Since the smoke detection system was to undergo major reconstruction, it was thought advisable to redesign the rather makeshift optical protective windows (i.e. at the points of entry and exit of the light beam through the chamber). The housings are shown in Figure 26(a) and (b), and were constructed from a non-magnetic, corrosion resistant grade of stainless steel (i.e. Type 316 Stainless, AISI Type EN 58 j), and normal picture frame glass, (the optical response of this glass shows it to be transparent for the whole of the visible region, and had a neutral optical density equivalence of 0.03 to 0.07; see Figure 24). In this construction both windows were heated by wound resistance-wire heaters, driven by a stabilised transformed mains supply (i.e. 240v to 12v) to give a window temperature of 60–80°C, (see Figure 25).

The heaters were usually turned on for at least 30 minutes before the beginning of a day's series of tests, to bring the windows up to temperature.
FIG 26A: SCALE DRAWING OF SMOKE DETECTOR'S UPPER HOUSING
FIG. 26B: SCALE DRAWING OF SMOKE DETECTOR'S LOWER HOUSING.
Figure 26(a) shows the upper housing which passed through the roof of the chamber, and screwed into the base of the optical bench. The heater was sealed into the base with silicone rubber, with its leads passing out of the walls of the cylinder forming the walls of the housing. A screw cap contained the plain glass disc sealed in position with silicone rubber, and when it was screwed up on to the housing it fitted flush with the heater. This housing was fixed in to position with cement, giving the optical bench additional anchorage and sealing the chamber. The upper housing was located vertically above the lower housing which is shown in Figure 26(b). This included a milled lip to seat the heater in position, and a lower lip for a lens (nominal focal length of up to 10cm). The lens has since been removed in the latest set up, since a condensed light beam readily swamped the photodetector at neutral optical density equivalent to 0.00. The photodetector was itself part of a sliding cylinder which has a three pin DIN plug in its base, for connection to the rest of the sampling amplifier and to the data logger. The sample detector was designed to move up and down in order to locate the best position for the fixed lens (when sited in the housing) and then it could be firmly fixed in the housing by a side screw. In operation the beam formed a 0.9 inch diameter image over the area of the photodetector, the position of the photodetector inside the housing was then perhaps less important. As a result it was secured at the bottom of the housing. The fine adjustment of the position of the lower housing was carried out using locating nuts about its circumference, acting on a steel ring fixed into the base of the chamber. The housing was then cemented into position.

(iv) Calibration

In the preliminary work, smoke was determined in terms of percentage obscuration, between a 0 and 100% scale on the chart recorder, which
was later converted to a rough value of neutral optical density.

Then a millivoltage equivalence of neutral optical density was
determined from smoke tests, based on calibration using Kodak
neutral optical density filters (calibrated in the Kodak laboratories
based on readings of a Macbeth-type contact opal densitometer to
BS 1384). Values are given in Appendix 6.

Since fine adjustment of the light output between each run was
required, the initial millivoltage output of the Darlington detector
was not constant. In order to save time the construction of a
conversion table (ie. millivoltage to neutral optical density equivalents
of smoke) was undertaken. The way this table was devised is given in
detail in Appendix 6. Table A.6.2 as shown in Appendix 6 was constructed
from values of millivoltage at neutral optical density equivalent of
0.000 from 1.00 to 23.00 millivolts. In operation the millivoltages
were tabulated from punch tape, the millivoltage at the neutral optical
density equivalent was established (ie. before burn started) and also
found down the first left hand vertical column of the table. The values
of the millivoltage with increasing smoke build-up are read off along
that horizontal line against the decreasing neutral optical density
of the top horizontal line.

(v) Soot Formation

During most tests soot was formed and was carried into the atmosphere
of the chamber be convection currents. Slowly, during and after
the test, these particles either precipitated to the floor or
became deposited on most other surfaces. Surprisingly, the thickest
deposits were found on the ceiling of the chamber, including the
upper protective window, rather than on the lower surface. With
the present of soot deposits the smoke level recorded had to be
adjusted accordingly, but as it was not possible to determine rates
of build up, this "soot-level" as a neutral optical density equivalent could only be substrated from a maximum recorded value of neutral optical density. This "soot level" was also used as a rough measure of soot generated during burn for these tests, but precision was lost since conditions of burn varied considerably. The presence of the soot also made it necessary to throughly clean the optical windows before starting a test.

8.2.5. Toxic Gas Monitoring

The original gas analysis equipment limited sampling to single analyses per gas per test. Sampling was conducted when the combustion was assumed to be complete. The single measurements were restricted to maximum concentrations of gas produced, with no idea of gas build up, or when gas release occurred during a test. The obvious remedy for these problems was continuous monitoring. The Dräger colourimetric analysis was limited to relatively high toxic gas concentrations relevant to exposures for eight hour periods in industrial atmospheres, with little or no sensitivity in the lower ranges of concentration. In addition Dräger tubes were slow to operate (particularly TDI or oxygen) especially when side reactions inside or leakage into the chamber might effect the final result.

(i) Availability of Continuously Monitoring Equipment

Finance limited selection of continuously monitoring equipment to a single item of equipment. Since the majority of tests were with polyurethanes it was felt that in relative order of importance for analysis, the gases were carbon monoxide, nitrogen dioxide, hydrogen cyanide and finally either carbon dioxide or oxygen depletion (81)
Equipment suggested is shown in Table 20:

**TABLE 20 : Suitable Continuously Monitoring Gas Analysers**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Instruments Trade Name</th>
<th>Manufacturer</th>
<th>Range (ppm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>IRGA 10</td>
<td>Grubb Parson</td>
<td>0 - 2500</td>
<td>NDIR. Most sensitive at higher range</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low shock resistance</td>
</tr>
<tr>
<td>CO</td>
<td>IRGA 20</td>
<td>&quot;</td>
<td>0 - 2500</td>
<td>As for IRGA 10</td>
</tr>
<tr>
<td>CO</td>
<td>Jungalor</td>
<td>Elliot Automation</td>
<td>0 - 2500</td>
<td>Portable. Scale can be altered by chopping beam</td>
</tr>
<tr>
<td>NO</td>
<td>IRGA</td>
<td>Grubb Parson</td>
<td>0 - 2000</td>
<td>Non-dispersive infra-red</td>
</tr>
<tr>
<td>HCN</td>
<td>IRGA</td>
<td>&quot;</td>
<td>?</td>
<td>Non-dispersive infra-red</td>
</tr>
<tr>
<td>NOx</td>
<td>Various</td>
<td>Bendix, Beckman,</td>
<td></td>
<td>Chemiluminescence principle of sampling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>British Oxygen Co.</td>
<td></td>
<td>Run at atmospheric pressure, need sampling system</td>
</tr>
<tr>
<td>O2</td>
<td>Various</td>
<td>Taylor, Servomax</td>
<td>0 - 20%</td>
<td>Paramagnetic sampling system</td>
</tr>
</tbody>
</table>

Note: The IRGA range of non-dispersive infra-red monitors can measure most gases desired. Grubb Parson's have several other non-dispersive infra-red carbon monoxide and dioxide analysers.

In addition it was felt a gas chromatograph system would be of little value for monitoring nitrogen oxides, hydrogen cyanide and most other reaction gases, as a gas chromatograph was a somewhat operator subjective test.

(ii) Sampling Unit

Discussions with the British Oxygen Company (82) produced most of the information discussed in Chapter 2.5.1. Therefore a carbon monoxide continuously monitoring unit was selected, based on Grubb Parson's SB2 Infra-red Gas Analyser, supplied with its own pump, flowmeter and facilities to monitor two ranges of carbon monoxide (ie. 0 to 0.4% or
FIG 27A: SCALE DRAWING OF GAS MONITORING EQUIPMENT.
FIG 27B: SCHEMATIC DIAGRAM OF GAS MONITORING EQUIPMENT.
FIG 28A:

IRGA 2B Analyzer Calibration
(a) Meter reading v.
Volume of CO.

FIG 28B:

IRGA 2B Analyzer Calibration
(b) Millivolt output v. volume of CO

FIG 28: IRGA 2B ANALYSER'S CALIBRATION CURVES
0 to 4000 ppm and 0 to 2.5% or 0 to 25,000 ppm by volume). The description, calibration and use of the equipment is described elsewhere (83).

The carbon monoxide analyser is shown in position in the sampling unit in Figure 27(a). The schematic diagram of the gas sampling unit is shown in Figure 27(b). Both pumps shown were run at similar flow rates, to prevent delays in response or increase sampling. To protect the carbon monoxide analyser from "poisoning" or particulate and oily contamination the following filters were included:

(a) coarse dust filters fixed in the conical funnels at the end of the sampling tubes, inside the chamber
(b) silica-gel water trap (changed normally after every third test)
(c) oil and dust extractor.

(iii) Calibration of IRGA SB2
The concentration of carbon monoxide present inside the chamber was displayed on a meter labelled 0 to 50 at the top of the IRGA SB2. A conversion chart supplied with the unit was then used to translate this into a concentration value (see Figure 28(a)). The meter was used for both ranges of carbon monoxide. The IRGA can be connected to a chart recorder, but this facility had been adapted to permit connection to a data-logger. Graphs 28(b) and (c) were constructed to give values of carbon monoxide in parts per million (ppm) directly from millivoltage. Delays in response of the analyser were evident due to both:

(a) length of tubing between chamber and IRGA
(b) electronic response of the IRGA.
FIG 28C:

IRGA 2B Analyzer Calibration
(\( \text{meter reading v millivoltage output} \))

FIG 29: IRGA 2B'S RESPONSE CURVES.
The delay in response was measured in the following manner:

(a) a standard mix of carbon monoxide/air (0.4% concentration) was released into the chamber, with the sampling taps closed to the chamber and opened to the outside atmosphere. The carbon monoxide was allowed to mix uniformly with the air in the chamber.

(b) the IRGA was started, and the data-logger turned on simultaneously with a stopwatch.

(c) the flowmeter of the IRGA was adjusted to 2.0 litres/minute and after one minute the tap from the chamber was opened for sampling. The gas was allowed to run until the meter reached a maximum and then for 30 seconds. The chamber was sealed off, and the sample tubing open to the atmosphere.

(d) the procedure was repeated for 1.5, 1.0 and 0.5 litres/minute flow rate.

(e) the whole procedure (ie. (b) to (d)) was repeated again for an increased length of sample tubing.

Figure 29 shows the results. At the flow and tubing length normally used (ie. 1.5 litres/minutes and 3.35 metres respectively), the initial response between carbon monoxide appearing inside the chamber and being recorded by the analyser was 15 seconds.

The carbon monoxide concentration was usually recorded on punch tape as a millivoltage, to be later drawn up as time versus millivoltage, and was then converted by adjustment of the millivoltage scale to parts per million of carbon monoxide.

(iv) Switch-over Unit

When large amounts of carbon monoxide were present, a range change could be carried out on the IRGA (ie. from 0 to 0.4% to 0 to 4%).
FIG 30: SWITCH-OVER UNIT FOR CARBON MONOXIDE MONITOR.

When the lower scale of CO reaches a maximum, the IRAA 20 is switched over to a larger range. At the same time the multiway switch is manually changed from 1 to 3 (these changing amplifier output from line 109 to 110 in the datalogger).

FIG 31: ELECTRICAL SWITCHBOARD CIRCUIT.
In order to show the range change on the data-logger, a separate line was used, using a simple switch-over unit. This had to be switched at the same time as the IRGA range was changed. The circuit for this data range change is shown in Figure 30; it was designed so that when a range was not in use, its output to the data-logger read 0.00 mV.

(v) Other Analysis

Work by Higgins (84) using the Chamber, involved the use of simple sampling equipment, i.e. evacuated flasks inserted into the sampling set up. When a burn was completed, air from the chamber was drawn into the flask by opening its valve. The valve was then closed with the flask containing a gaseous sample. This was either run into an infra-red gas cell for spectroanalysis, or into a mass spectrometer for radical analysis.

For analysis of gases other than carbon monoxide, Dräger tubes continued to be used.

8.2.6. Data-Logger

The data-logger was set up to monitor in the order shown in Table 21.

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Apparatus Monitored</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Smoke</td>
</tr>
<tr>
<td>1</td>
<td>Thermocouple mid bottom (ref.TC1)</td>
</tr>
<tr>
<td>2</td>
<td>&quot; mid middle (ref.TC2)</td>
</tr>
<tr>
<td>3</td>
<td>&quot; mid top (ref.TC3)</td>
</tr>
<tr>
<td>4</td>
<td>&quot; back bottom (ref.TC4)</td>
</tr>
<tr>
<td>5</td>
<td>&quot; back middle (ref.TC5)</td>
</tr>
<tr>
<td>6</td>
<td>&quot; back top (ref.TC6)</td>
</tr>
<tr>
<td>7</td>
<td>Carbon Monoxide Analyser (0 to 0.4%)</td>
</tr>
<tr>
<td>8</td>
<td>&quot; (0 to 4%)</td>
</tr>
<tr>
<td>9</td>
<td>Unused line</td>
</tr>
</tbody>
</table>

The data-logger was set to produce the data tabulated in the following form:
FIG. 32: SCALE DRAWING OF CHAMBER'S EXTERIOR.
where the first four digits are time of test, the first two figures being the hour, the other two the minutes. The long row of figures may be interpreted as the first digit of each group of numbers being the line number, and the next four digits being the value of millivoltage multiplied by 100. The cycle between a display of figures was normally 10 seconds, and each line was displayed at the time during a minute shown in Table 22.

TABLE 22:

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Times During a Minute at which Data Printed in Groups of 10 seconds (in seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st Group</td>
</tr>
<tr>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>0.75</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>1.25</td>
</tr>
<tr>
<td>6</td>
<td>1.50</td>
</tr>
<tr>
<td>7</td>
<td>1.75</td>
</tr>
<tr>
<td>8</td>
<td>2.00</td>
</tr>
<tr>
<td>Time. Printed at (sec)</td>
<td>9.00</td>
</tr>
</tbody>
</table>

8.2.7. Electrical Supply

The majority of equipment used was supplied with mains voltage which was transformed, normally rectified and voltage stabilised. To minimise the number of trailing cables about the rig, a switch-board was designed and built. Its circuit diagram is shown in Figure 31. Each separate circuit was individually fused and switched. In addition a 13 amp socket was included for maintenance or temporary installations.

A photograph of the rig is shown in Appendix 3. The final front view of the chamber is shown in Figure 32. The operation of the test rig is given in Appendix 6.
CHAPTER 9 : DESIGN TESTING
9.1 Concepts of Testing

The preliminary work had shown that the rig in a modified form could have potential as the basis of a "medium scale" fire test. In the discussion of results stemming from the preliminary test (see Chapter 7.4) the relevance of the early work has been discussed and in comparing with the Inter-Company Urethane Panel work the following conclusions were drawn:

(a) the test gave the same relative scaling of the flammability properties of the materials (i.e. had a qualitative property)

(b) there was only limited parallelling of the various parameters, particularly with gas levels and lower temperatures recorded (i.e. A quantitative method had not been established).

The quantitative status was difficult to achieve since there were major differences between the variables of the mid and large-scale tests. To establish a quantitative status with the reconstructed rig, it was suggested the following be carried out:

(a) tighter controls on variables in a test

(b) flexibility of the test rig allowing any possible number of changes in the test method (e.g. variation of sample geometry or ignition source).

The possible fixed and variable properties of a mid scale test burning furnishing materials were identified as follows:

Fixed Properties (permanent through the whole of the tests):

(a) volume of filler and surface area of fabric covering

(b) volume of chamber and hence initial air supply, (although these could be varied at some later stage)

(c) initial chamber temperature (i.e. 23 ± 5°C)

(d) monitoring positions of all the sampling equipment in relation to the chamber.
Variable Properties (fixed only at the start of each test, but adjustable if desired):—

(a) ignition source; variation achieved by selection of a typical ignition source, eg. burner flame (of varying flame size, composition and temperature), burning newspaper, lighted matches, smoldering cigarettes, etc.

(b) ignition position

(c) geometry of filler; variation here possible in a number of ways, ie. in relationship to the ignition source and sampling positions, or varying of surface area of sample (although fabric surface area was fixed)

(d) composition of test piece (eg. in this work there was a variety of five fillers with and without any of the five fabric coverings).

It was hoped to determine the flexibility of the chamber by experimenting mainly with the variable properties, and perhaps find the setting up requirements to produce real-life fire conditions. To complete the assessment of the materials supplied, typical small-scale fire tests were carried out (including critical oxygen index). The relevance of differential thermal and thermogravimetric analyses was also determined.

9.2. Mid-Scale Testing

9.2.1. Burner Ignition Source and Sample Holder Design

(i) Burner Design and Use

This particular work continued from where the preliminary tests left off. With the introduction of a controllable gas ignition system with some flexibility (in terms of gas composition, flame shape and temperature), it was hoped that a fuller burn (ie. to completion) of a test sample could be achieved. The standard 7.5 x 20 cm$^2$ uncovered non fire retarded foam sample was used throughout these tests.
FIG 33: RELATIVE POSITIONING OF FLAMELETS ON A 7.5X20^2 CC VERTICAL SAMPLE.
FIG 34: SCALE DRAWING OF SEVEN-WAY BURNER.
Prior to starting any burns, the true flow ratio of the ignition lines were determined, since it was assumed there would be pressure drop due to leaks between the mixing unit and the burner. This is described in Appendix 8.1.

In the preliminary work the single flame produced by the ignition source positioned under the sample resulted in the shapes of burn pattern indicated in Figure 15. A single flame seemed to produce a "horseshoe" burn pattern in the uncovered sample, which then developed in a fuller burn with the more flammable polyurethane foams (e.g. non fire retarded foam). It was felt a burner, in the form of a number of flamelets, acting along the whole base of a sample, might produce a uniform spread of burn during test. The spread should move primarily up through the sample, rather than up and sideways as found in the earlier tests. The increased number of ignition points should, in theory, produce a fuller burn.

To prevent blockage of the flamelets (of $\frac{3}{8}$ inch internal diameter), the burner was designed to act on the lower front edge of the sample. In addition the design had to include at least one flamelet playing into a tray collecting liquids from the burning sample, so that the liquid could be burnt to add to the fuel content of the burn. To counteract the initial "horseshoe" shape of the burn pattern the flamelets were positioned on the sample and into the drip tray as in Figure 33.

The final design of a seven way burner is shown in Figure 34. The mixed gas fuel was fed into the back of the mixing chamber. Equally placed around the chamber were seven copper pipes ($\frac{3}{8}$ inch internal diameter) of equal length, bent to give the gas exit pattern as shown in Figure 33. Each of these tubes had a simple screw valve, used to adjust the length of the flame of each flamelet, so all seven flames
FIG 35: DESIGN OF HOLDER FOR 7.5X20°CC VERTICAL SAMPLE.
were of the same length.

(ii) Sample Holder Design

The primary requirements of the sample holder were thought to be:

(a) flexibility of design, which demanded a construction that could be easily reassembled for a different geometry of sample, or positioning inside the chamber

(b) permanence of shape while a large number of samples were subjected to a single type of test

(c) non-flammable and non-deformable structure (suggesting unpainted steel)

(d) minimum (preferably none) interaction with the fire reaction, i.e. the maximum of sample support and stability was given (preventing collapse) with the minimum of structural interference, (e.g. no heat loss to structure desired)

(e) could be fixed to the anchor frame in the base of the chamber.

A 'Meccano' structure met most of these requirements.

The drip tray for collecting burning droplets or liquid from the burn area above, was simply constructed from stainless steel plates rivetted together, and angled to aid flow down to the flamelets. This tray along with the sample holder used for testing a 7.5 x 20^2 cm^3 upright sample is shown in Figure 35. With the seven-way burner in position the determination of maximum flamelet temperature was carried out; this is described in Appendix 8.2.

(iii) Examination of Seven Way Burner as An Ignition Source

(a) Run One

Using the standard vertical uncovered non-fire retarded sample (as shown in Figure 35), the burner was positioned to give uniform
FIG 36: TYPICAL BURN PATTERNS USING THE SEVEN-WAY BURNER.
contact with the lower edge. The ignition gases were turned on (150 : 2500 cc/min by volume propane to air, uncorrect flow), and each flamelet was quickly ignited; these were left on throughout the test. Only visual observations were made.

The sample was instantly alight across its exposed vertical face. Although the flame was extinguished here in 2.5 minutes, flame continued at the top of foam moving gradually downwards. The fire was completely out after 7.5 minutes. Approximately 20 per cent of the sample remained as shown in Figure 36 (Run One).

The downwards pointing flamelets had little effect on igniting the oily residue formed.

(b) Run Two

In this run the hottest stable flame possible (ie. 150 : 2800 cc/min by volume propane to air, uncorrected flow) was used. A flexible thermocouple was inserted into the centre of the non fire retarded sample.

Observations showed that the foam initially exposed burnt away so rapidly that the flamelets were not effectively impinging on the sample after 20 seconds. After 2.5 minutes the thermocouple recorded a temperature maximum at the burn centre of 550°C. Burning of some of the oil residue occurred after 3.0 minutes at which point the top of the foam stopped burning. The flame was out completely after 4.0 minutes. There was no evidence of after burn (ie. glow or smoldering).

Approximately 15 per cent of the sample remained, with less oil remaining than in Run One, as shown in Figure 36 (Run Two).
(c) Run Three

A relatively hot and large flame was used (150 : 1800 cc/min by volume propane to air, uncorrected flow) which gave a longer flamelet impingement on the sample.

Again there was rapid burn away from the flamelets, the thermocouple indicating a maximum temperature of 700°C. The foam collapsed forward over the flamelets which, in this case aided the burn; the burn was completed on the floor of the chamber. The total burn time was 5.5 minutes. There was less than 5 per cent of the foam left, coming from the lower back corners of the sample, plus the usual oil.

On repeating this test, the thermocouple reached 660°C after 1.5 minutes and the fire was extinguished in 4.5 minutes leaving 10 per cent of the foam. Carbon monoxide measured indicated a maximum of 700ppm.

(d) Comments on the Three Runs

In employing the non fire retarded foam sample, it was hoped with its high flammability, ideal fire conditions would produce a full burn, without the complications of fabric interactions. Only the first sample used in Run Three came close to a full burn; this showed two things:

(1) repeatability of the test was effected by instability of sample during the burn
(2) the air present inside the chamber was enough to produce at least 95 per cent consumption of a sample in a combustion burn.

Some conclusions and questions arose from this work, and are therefore relevant to future work, namely:

(1) with a fixed hot ignition flame the non fire retarded foam rapidly
burnt away from the source. (The flamelets then only heated the atmosphere apparently with no other effects on the burn). In the preliminary tests the larger flame acted on the sample for a longer period.

(2) Although the ignition produced in the vertical geometry of the samples was of the limited self-supporting type, spread could have been effected by either char formation or oil take-up by the foam. The oil having a high flash point, was not ignited by the fire in the sample (ie. by the heat from the ignition source or the burning sample itself).

(3) Igniting one side of the sample did not produce complete burning and as siting the burner under the sample had associated problems, an ideal burner set up would have been with duplicate burners either side of the sample. The sample should have been clamped to ensure it remained static throughout the test. However, clamping would have inhibited fire spread and made an unlife-like method of test. In addition, using two burners on either side of the sample would produce a problem of siting the sample before the ignition started.

(4) There was a contradicting question of whether the sample should remain static during test or be allowed to collapse in a manner dictated by the random nature of burn path (ie. either into or away from the fire centre, producing differing fuel contributions). For repeatability the sample should have remained static as in many small scale fire tests. However, in real-life tests, sample collapse occurred at random.

(5) Oil lost was significant in two ways: there was oil lost away from the fire centre taking some heat as well, and oil as a potential fuel source was leaving the area where it could have been converted by heat into flammable gas. Even with the redesigned sample
holder, it being nearer to the floor of the chamber, the fire centre was still too high to ensure oil ignition under these conditions.

(6) Employing a hot gaseous ignition source may be questioned. Few full scale fires have been caused by prolonged exposure to a Bunsen flame. The test as it stands probably paralleled small scale tests with use of a burner ignition source. Comment may be made, questioning the use of the hot flame in these tests, when realistic fire comparisons were to be made. In real-life fires, the cause of ignition was due mainly to longer exposure to a cooler flame generated by a solid or liquid source (ie. burning paper, matches or petroleum), laying on or under the sample.

(7) Finally, was the surface area of sample initially exposed large enough to produce adequate fire spread? The ratio of surface area of sample to volume in these tests was 2.80 : 6, which in fact was less than that of the RAPRA II test (1.64 : 6) and decreasing surface area any further became even less realistic. There was, however, some justification in decreasing the ratio, so the flame produced in the sample would act over more of its surface rather than being lost above it, (ie. paralleling the full scale test where the flame acted on the surface rather than being lost to air).

9.2.2. Morphological Effects in Fire Tests

(i) Test Methods

The morphological effects on the sample in relationship to its geometry position in the chamber, and position in terms of ignition source and monitoring apparatus were next studied.
**Ref**  | **Front Elevation** | **Top Elevation** | **20° Projection**

**FIG 37A:** TYPICAL SYMMETRICAL GEOMETRIES OF FOUR PIECE SAMPLE.
FIG 37B: TYPICAL SYMMETRICAL GEOMETRIES OF THREE PIECE SAMPLE.
FIG 37C: TYPICAL SYMMETRICAL GEOMETRIES OF THREE PIECE SAMPLE.

(OPE PIECE CUT EQUALLY INTO TWO PIECES)
FIG. 37D: TYPICAL SYMMETRICAL GEOMETRIES OF TWO PIECE SAMPLE.
In any real-life fire, a complex geometry of composite is exposed to fire (e.g., a mix of vertical, horizontal and inclined surfaces).

However, in these tests a limited number of sample forms were tested i.e., $7.5 \times 20^2 \text{cm}^3$ geometry for all fillers and a non fire retarded foam sheet. The latter was cut to a thickness of 2.5cm, allowing it to be cut into a number of shapes. The variety of symmetrical geometries considered are shown in Figure 37 along with values of volume, total surface area, "exposed surface area" and "internal surface area".

The latter two areas are defined as follows:

(a) exposed surface area is the area of foam visible from all angles of observations

(b) internal surface area is the area of foam that is immediately exposed to fire, if the ignition source is placed on the largest horizontal face.

Since other work (29), examining flammability in terms of critical oxygen index suggested the maximum flame spread rate resulted in spread up a vertical surface, the test piece selected had relatively large areas of vertical surface exposed to fire.

The following tables 23(a) to (d) show what tests were carried out in the examination of sample "morphology".
SAMPLE 2.8:

Cube = 14.43 cc in volume
(made up of six thicknesses of ~2.5 cm wide foam)

SAMPLE 2.9

SAMPLE 2.12:

SAMPLE 2.13:

FIG 38: MAXIMUM & MINIMUM VERTICAL SURFACE AREAS OF SAMPLE.
### TABLE 23(a) : Selection of Ignition Source and Ignition Source Position with Geometry Variation

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Geometry Reference</th>
<th>No. of Pieces</th>
<th>Ignition Source</th>
<th>Ignition Position</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>lc</td>
<td>4</td>
<td>Lighted Match</td>
<td>Centre of Back Face's Base</td>
<td>NFR alone</td>
</tr>
<tr>
<td>2.2</td>
<td>lc</td>
<td>4</td>
<td></td>
<td>Centre of a side Face's Base</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.3</td>
<td>lc</td>
<td>4</td>
<td>One Piece of Burning Newspaper</td>
<td>Top Centre of Base</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.4</td>
<td>3c</td>
<td>4</td>
<td>Lighted Match</td>
<td>Centre of Back Face's Base</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.5</td>
<td>3c</td>
<td>4</td>
<td>One Piece of Burning Newspaper</td>
<td>&quot;&quot; &quot;&quot; &quot;&quot;</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.6</td>
<td>2c</td>
<td>3</td>
<td></td>
<td>Apex Formed by Three Pieces Meeting</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.7</td>
<td>lc</td>
<td>4</td>
<td>Two Pieces of Burning Newspaper</td>
<td>Centre of Sides Face's Bases</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.8</td>
<td>Cube (14.45 cm³)</td>
<td>1</td>
<td>One Piece of Burning Newspaper</td>
<td>Top Central</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.9</td>
<td>&quot;&quot; &quot;&quot;</td>
<td>1</td>
<td>&quot;&quot; &quot;&quot; &quot;&quot;</td>
<td>Centre of a side Face's Base Top Central</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.10</td>
<td>20²x7.5cm²</td>
<td>1</td>
<td>&quot;&quot; &quot;&quot; &quot;&quot;</td>
<td>Centre of 25cm Base</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.11</td>
<td>25x48x2.5</td>
<td>1</td>
<td>&quot;&quot; &quot;&quot; &quot;&quot;</td>
<td>Centre of 25cm Base</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.12</td>
<td>20x60x2.5</td>
<td>1</td>
<td>&quot;&quot; &quot;&quot; &quot;&quot;</td>
<td>Centre of 25cm Base</td>
<td>&quot;&quot;</td>
</tr>
<tr>
<td>2.13</td>
<td>15x80x2.5</td>
<td>1</td>
<td>&quot;&quot; &quot;&quot; &quot;&quot;</td>
<td>Centre of 25cm Base</td>
<td>&quot;&quot;</td>
</tr>
</tbody>
</table>

Figure 38 shows the set ups used for 2.8, 2.9, 2.11, 2.12 and 2.13.
### TABLE 23(b) : Special Modifications

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Geometry Reference</th>
<th>No. of Pieces</th>
<th>Ignition Source</th>
<th>Ignition Position</th>
<th>Modification</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.14</td>
<td>1c</td>
<td>4</td>
<td>Two Pieces of Burning Newspaper</td>
<td>Centre of Side Faces Base</td>
<td>False Ceiling (30cm from Base)</td>
<td>NFR alone</td>
</tr>
<tr>
<td>2.15</td>
<td>1c</td>
<td>4</td>
<td>&quot; &quot; &quot; &quot;</td>
<td>&quot; &quot; &quot; &quot;</td>
<td>&quot; &quot;</td>
<td>&quot; &quot;</td>
</tr>
<tr>
<td>2.16</td>
<td>20^2 x 7.5cm^3 Horizontal</td>
<td>1</td>
<td>One Piece of Burning Newspaper</td>
<td>Top Central</td>
<td>False Ceiling (40cm from Base)</td>
<td>&quot; &quot;</td>
</tr>
<tr>
<td>2.17</td>
<td>1c</td>
<td>4</td>
<td>Two Pieces of Burning Newspaper</td>
<td>Centre of Side Faces Bases</td>
<td>False Ceiling (30cm from Base)</td>
<td>&quot; &quot;</td>
</tr>
<tr>
<td>2.18</td>
<td>1c</td>
<td>4</td>
<td>One Piece of Burning Newspaper</td>
<td>Bottom Mid Face</td>
<td>Aluminium Covered False Ceiling (30cm from Base)</td>
<td>&quot; &quot;</td>
</tr>
<tr>
<td>2.19</td>
<td>1c</td>
<td>4</td>
<td>Two Pieces of Burning Newspaper</td>
<td>Centre of Side Faces Bases</td>
<td>Wooden Sample Holder</td>
<td>&quot; &quot;</td>
</tr>
</tbody>
</table>

### TABLE 23(c) : Fabric Covering Effect on Non Fire Retarded Foam Covered in 1(c) Type Geometry

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.20</td>
<td>Cotton-acrylic</td>
</tr>
<tr>
<td>2.21</td>
<td>Wool</td>
</tr>
<tr>
<td>2.22</td>
<td>Wool (with glasscloth)</td>
</tr>
<tr>
<td>2.23</td>
<td>Cotton-acrylic (with glasscloth)</td>
</tr>
<tr>
<td>2.24</td>
<td>Wool-rayon (with glasscloth)</td>
</tr>
<tr>
<td>2.25</td>
<td>Polyurethane (with glasscloth)</td>
</tr>
</tbody>
</table>

Ignition Source: Two Pieces of Burning Newspaper Positioned at the Centre of Side Faces' Bases
<table>
<thead>
<tr>
<th>Test Ref</th>
<th>Foam</th>
<th>Fabric</th>
<th>Sample Position</th>
<th>Ignition Position</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.26</td>
<td>NFR</td>
<td>-</td>
<td>Vertical</td>
<td>Centrally under</td>
<td>Sample</td>
</tr>
<tr>
<td>2.27</td>
<td>FR</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.28</td>
<td>FR</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.29</td>
<td>L</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.30</td>
<td>NH</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.31</td>
<td>NFR</td>
<td>W-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.32</td>
<td>&quot;</td>
<td>C/A-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.33</td>
<td>&quot;</td>
<td>W/R-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.34</td>
<td>&quot;</td>
<td>PU-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.35</td>
<td>&quot;</td>
<td>PVC-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.36</td>
<td>NH</td>
<td>W-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.37</td>
<td>&quot;</td>
<td>C/A-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.38</td>
<td>&quot;</td>
<td>W-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.39</td>
<td>&quot;</td>
<td>C/A-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.40</td>
<td>&quot;</td>
<td>W/R-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.41</td>
<td>&quot;</td>
<td>PU-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.42</td>
<td>&quot;</td>
<td>PVC-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.43</td>
<td>NFR</td>
<td>-</td>
<td>&quot;</td>
<td>Centrally under</td>
<td>&quot;Closed&quot; Frame</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Base</td>
<td></td>
</tr>
<tr>
<td>2.44</td>
<td>&quot;</td>
<td>W-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.45</td>
<td>&quot;</td>
<td>W/R-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.46</td>
<td>&quot;</td>
<td>-</td>
<td>&quot;</td>
<td>&quot;</td>
<td>Open Frame</td>
</tr>
<tr>
<td>2.47</td>
<td>&quot;</td>
<td>W-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.48</td>
<td>&quot;</td>
<td>C/A-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.49</td>
<td>&quot;</td>
<td>W/R-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.50</td>
<td>&quot;</td>
<td>PU-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.51</td>
<td>&quot;</td>
<td>PVC-GC</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>2.52</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 23(d) : Comparison of Fabric Covered Fillers with Variation of Ignition Position

A 7.5 x 20²cm³ Sample Used, With One Piece A4 Paper as an Ignition Source.

In all this work full monitoring of fire parameters was carried out, following the test procedure described in Appendix 7. The data was punched out on tape then transcribed on to paper as tables of millivolts which, in turn, were converted to meaningful monitored values by graphical
FIG 39: TYPICAL 'MECCANO' FRAME

Note: Sample Frame Not Shown.
(a) Distances x, y, z used to precisely locate sample when frame is not anchored
(b) The ignition sites are indicated in A. (c) Geometry is: (A); middle of the base of the vertical back wall piece, (B); centrally placed on the top of the horizontal base piece, (C); middle of the base of a diagonal piece (and all emitted side wall with a paper igniter), (D) 0e open formed by three pieces of Geometry 2.0.

FIG 40: LOCATION OF SAMPLE IN CHAMBER.
representation. In addition to the monitoring, the following were carried out:

(a) visual observation of the burn
(b) weight loss of the sample determination
(c) free-hand sketching of the remains after a burn, to estimate burn path and pattern.

(ii) Notes on Morphology Studies
The multipiece sample had to be accurately positioned in the chamber, employing the sample holder to ensure repeatability. Typical design of frame is shown in Figure 39, indicating the open structure of the holder. Each piece of the filler was held in position by sewing to the 'Meccano framework with nylon upholstery thread.

The relative positioning of the sample inside the chamber, and the placing of the ignition sources is shown in Figure 40.

The initial temperature recorded at thermocouple I should reflect the positioning of the ignition source(s) in the sample (ie. ignition sources vary in position relative to the thermocouples).

The ignition sources used were limited to:

(a) those of relatively low temperature
(b) those of relatively long burn time
(c) solids which remain longer in contact with the surface of the sample in comparison to the burner flame.

Typical domestic fire initiators were selected from those used in the Inter-Company Urethane Panel tests, ie. lighted matches or newspaper. Neither of these ignition sources could be guaranteed to burn steadily.

A question arose of in what quantity and in what form the paper should be used. In the Inter-Company Urethane Panel tests three full sheets
of Daily Mirror newspaper (ie. 3 x A2 size or a total of 82,800 sq.cm.) were balled up and placed on the seat of one of the test chairs.

Newspaper is a cheap form of cellulose. In realistic scaling down of the source approximately 1/90th of the original fire load of paper (or $9.5^2 \text{cm}^2 = 92 \text{ sq.cm}$) should have been used, but the resulting ball would have been very small and have had little contact area with the sample. In a somewhat arbitrary manner, an A4 piece (ie. $20.5 \times 30 \text{cm}^2$) balled up was selected, using paper from half a page of a daily newspaper.

Some tests were carried out to determine the mode of burning of the paper in regard to the size of ball and hence the degree of compression. The more compressed the paper, the less air was available in the folds of the paper and the rate of burn was slowed down even to the extent that the paper did not burn completely (in any case charred paper was left), and a drastic fuel contribution change occurred. A ball compressed gently and then allowed to 'relax' back to an egg-shape of 4 by 5 cm, was found to be the best shape to give fair repeatability of test. Having a slightly flattened ball prevented rolling about inside the sample when alight. Test number 2.52 showed that the paper produced insignificant amounts of carbon monoxide, smoke and only a small temperature rise inside the chamber.

The match, though originally thought to be a consistent source, was dropped in favour of the paper (the latter being a greater fire load and easier to position). No data was generated on the burn characteristics of the match.

The effect of the newspaper ignitor on several geometries, ranging from the samples of large surface area (eg. 1c, 3c or 2c) where the sample overall occupied a relatively large volume of chamber space to the low surface area sample (eg. $14.4^3 \text{cm cube}$) occupying a compact 175
volume were examined. In addition single pieces of foam of large area of vertical face were tested, (ref. 2.11, 2.12, 2.13). A full discussion of burn pattern, and fire characteristics can be found in Chapter 10, but the following facts were of relevance to future tests:

(a) the paper produced a longer burn and therefore a more complete combustion. Since the paper had greater contact area and longer burn time than a match, its sitting on the sample and burn time on the sample was more repeatable

(b) in comparing Jb and lc geometries, there was little difference in burn characteristics, but lc was selected having offered an easier means of setting up the test sample. The 2c geometry gave the smallest burn

(c) a single paper source placed at position A, in geometry lc gave the most complete burn (with all of the back wall burnt away), and in position C a complete side wall was burnt (see Figure 40). Therefore by increasing the ignition source to two pieces of paper sited in both positions C did in fact produce a far more complete burn

(d) as long as it remained in position, the large vertical surface area sample rapidly burnt to near completion, but handling and fixing problems were great. The more compact geometries of sample gave poorer burns

(e) the large surface area samples (e.g. lc) appeared to lose a considerable amount of heat (in the form of flame) which was dissipated into the air of the chamber, leaving foam and considerable oily residue. In the Inter-Company Urethane Panel rig, the ratio of sample height to that of the ceiling was far smaller than that of the present test, and the heat generated from the sample was more
likely to act on unburnt material (the volume of air between ceiling and sample reaching far higher temperatures and consequently effecting the temperature of the test piece)

(f) the metal frame may contribute to other heat losses, as exhibited by the foam left in the corners of the sample holder.

(iii) Special Modifications

(a) False Ceiling

A large false ceiling was constructed from asbestos sheet, supported on four "Lab Lox" legs remote from the fire site. It was designed and made to:

1) reduce the ratio of ceiling height to height of test piece and retain the heat of combustion in the immediate area of the sample
2) allow air to circulate around the test area from the full capacity of the chamber. The position of the false ceiling is shown in Figure 17 (page 114). The board was 50cm square and was positioned centrally and horizontally either 30 or 40cm above the base of the chamber.

Only slight improvement in the burn was produced, and thus as a check to see if heat loss was actually significant the asbestos base and ceiling were covered with highly reflective aluminium foil. This produced near completion in burn and the highest temperatures recorded at thermocouple TCl. Even with this improvement of burn, the idea of employing a false ceiling was dropped as being impractical, and somewhat artificial especially with the use of the reflective surfaces.
FIG. 41: CONSTRUCTION OF WOODEN SAMPLE HOLDER.
These tests indicated that the chamber geometry was more important than originally thought.

(b) Alternate Sample Holder Materials
In assuming the metal framework of the 'Meccano' effected the burn pattern, a search was made for an alternative material, which met the following requirements:

1. strong, constructional material, easily fabricated into any desired form
2. low heat conductivity
3. reasonably fire resistant.

Though not fully meeting these, a pinewood construction was investigated; the design of holder is shown in Figure 41. The uncovered geometry of sample was fixed to the frame by looping thread around the upper horizontal slats and through the walls of the sample.

Results showed the following:

1. there was only a slight improvement in burn, although the fire interacted more with the foam in the corners of the holder
2. the frame was not damaged at all in the fire, again indicating rapid heat loss away from fire site. In fact the wood was not even charred by the flames
3. the frame was a fairly unstable structure, and proved less convenient for use as a sample holder than the 'Meccano'.

In the rest of the work, the 'Meccano' frame was used.
FIG. 42: POSITIONING OF FABRIC & IGNITION SOURCE IN A 1C SAMPLE GEOMETRY.
FIG43: FABRIC TEMPLATES USED IN PRESENT TESTS.
(iv) Fabric Covered Non-fire Retarded Foam in Geometry 1c.
The effect the covering had on the fire properties of the filler in the open geometry of 1c was examined. As in the preliminary work a problem arose of how to cover the sample to produce relevant information. Initially the fabric (17.3 x 28.6 cm²) was placed onto the sample previously sewn to the sample holder (See Figure 42).

Wool was used in the first run and was found to burn slowly, but cotton-acrylic readily produced large flames that quickly jumped (rather than spread) to the exposed foam. Therefore to prevent this flashover, a tissue glasscloth on areas of fillers not covered by the test fabric was used. The fabric and glasscloth were cut to size as shown in the Figure 43. The edge of the fabric was stitched to the edge of the glasscloth and wrapped around the piece of filler, as tightly as possible in order not to deform the filler. The fabric was fully united to the glasscloth (with slight underlapping of the cloth) by sewing into the foam. The four pieces of the sample were then sewn into the test frame. Two 2.5 x 17.4 cm² edges of each piece were left exposed, since they were well away from the initial fire centre.

(v) Comparison of Filler and Fabric Compositions
The multipiece geometry of sample, showed little if anything could be gained over the originally used 7.5 x 20² cm³ test piece; and therefore the single piece samples were used for the rest of the tests. However, these differed from the preliminary tests, as the paper ignition source was used to initiate the fire, (ie. one piece of A4 newspaper).
FIG 44A: VERTICAL.

FIG 44B: HORIZONTAL, (IGNITION UNDER SAMPLE).

FIG 44: HOLDERS USED WITH 7.5X20°C SAMPLES.
Three positions of sample in relations to the ignition source were examined, ie:

(a) vertical, with the base 5cm from the asbestos floor.

This allowed the paper to be in contact with floor and touching the sample. The middle set of thermocouples were centrally and immediately above the sample. Figure 44(a) shows the sample frame used. This was used to give some idea of what happens when a fire spreads up vertically through an upholstered back of a chair.

(b) horizontal, with the single A4 ball of paper placed centrally on top of the sample, with the thermocouples immediately above this. The base of the sample sat directly on the asbestos floor, and as such was unrealistic in that there was not an air gap (between floor and base) to parallel a fire in the seat of the chair.

(c) horizontal, with the single A4 ball of paper placed centrally beneath the base of the sample. The gap between the floor and base of sample was 5cm. Here the problems of precise positioning and the ignition of the paper arose, but as sets of results were repeatable this problem was assumed to be minimal.

The sample frame used is shown in Figure 44(b), but this proved too restrictive in that flame spread was stopped at the upper angle used to clamp the corners of the sample. This effect was adequately reduced by removing the upper part of the frame, so that the sample was only supported by the base.

Results are shown in Appendix 1.2.
9.3 Smoldering Tests

9.3.1. Concepts

In all previous tests the ignition source had been a relatively hot flame, but little was known of the reaction of these compositions to a smoldering source, (ie. that without flame). Two schemes of tests were possible:

(i) smoldering by inserting a sample into a heated chamber (ie. at a fixed temperature, above 200°C); this was equivalent to a macro-thermal analysis test. This method was not considered since it was unlife-like and therefore out of context in terms of this work, and also it would have been difficult to carry it out without major modifications to the apparatus

(ii) induce smoldering by an outside source in contact with a point on the surface of the sample. The choice of source varied from a hot electric filament (parallelling the ignition source of the AMINCO NBS type) to burning cigarettes.

Although both have contributed to initiating domestic fires, the latter was selected since:

(a) cigarettes contribute to far more fires than electric heaters

(b) design and construction problems of an electric heater (ie. producing repeatability and additional design of calibration equipment)

(c) cigarettes are produced by their manufacturers to a high level of quality control, and as such should be an ignition source(s) of high repeatability.
9.3.2. Smoldering Tests

Two types of cigarettes were selected and these are shown along with certain relevant properties in Table 24:

**TABLE 24 : Properties of Cigarettes Used**

<table>
<thead>
<tr>
<th>Trade Name</th>
<th>Diameter (cm)</th>
<th>Overall Length (cm)</th>
<th>Tobacco Length (cm)</th>
<th>Cigarette Weight (g)</th>
<th>Tobacco Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embassy Filter Tip</td>
<td>0.8</td>
<td>7.2</td>
<td>5.5</td>
<td>0.96</td>
<td>0.78</td>
</tr>
<tr>
<td>Rothman's King Size Filter Tip</td>
<td>0.8</td>
<td>8.4</td>
<td>6.4</td>
<td>1.02</td>
<td>0.85</td>
</tr>
</tbody>
</table>

The Embassy filter tipped cigarettes was chosen as it is a market-leader in the United Kingdom and the Rothman's as a means of examining the increase of fire load of the ignition source.

In some respects the use of a 'full-scale' cigarette as an ignition source, gives most tests values as limited full-scale tests. Therefore on this basis, it was felt that the test sample size would not be as crucial as in previous tests. It was thought possible, with a likely slower rate of fire spread, the smolder would be equivalent to the initiation and propagation stages of a full scale smolder. Assuming the fire does occur, the test would only be limited by the material available and the air apply. Test samples were constructed without consideration of material fire load, from the material geometries available.

The smoldering tests carried out are as shown in Tables 25(a) to (e).
FIG 45A: Simulation of a cigarette falling down the back of a chair (typical 1 geometry) with a temperature meter.

FIG 45B: Simulation of a cigarette sandwiched between two pieces of foam (type 2 geometry) with foam supported to give uniform air gap around the cigarette.

FIG 45C: Diagram showing position of bottom-middle thermocouple (see above center of test piece) with air flow.

FIG 45: SCHEMATIC DIAGRAMS OF SOME SMOLDER TEST SET-UPS.
### TABLE 25(a) : Study of Cigarette Smolder Characteristics

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Cigarette</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Embassy</td>
</tr>
<tr>
<td>3.2</td>
<td>Rothman</td>
</tr>
</tbody>
</table>

### TABLE 25(b) : Varying Geometry of Sample

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Geometry</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>Type 1</td>
<td>Flexible Thermocouple 2cm Below Base Piece's Upper Surface</td>
</tr>
<tr>
<td>3.4</td>
<td>Type 1</td>
<td>Flexible Thermocouple at Base Piece's Upper Surface</td>
</tr>
<tr>
<td>3.5</td>
<td>Type 2</td>
<td>Recess Made in Upper and Lower Piece To Seal Cigarette Completely In</td>
</tr>
<tr>
<td>3.6</td>
<td>Type 2</td>
<td>Recess Made Only in Base Area</td>
</tr>
<tr>
<td>3.7</td>
<td>Type 3</td>
<td></td>
</tr>
</tbody>
</table>

Notes: (1) Geometries 1 and 2 are shown in Figure 45(a) and (b)
(2) Uncovered non fire retarded foam only used, with Embassy Cigarettes in Still Air.

### TABLE 25(c) : Smoldering Tests Comparing Uncovered Fillers

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Filler</th>
<th>Cigarette</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>Non fire Retarded Foam</td>
<td>Embassy</td>
</tr>
<tr>
<td>3.8</td>
<td>Fire retarded Foam</td>
<td>Embassy</td>
</tr>
<tr>
<td>3.9</td>
<td>High Resilience Foam</td>
<td>Embassy</td>
</tr>
<tr>
<td>3.10</td>
<td>Latex Foam</td>
<td>Embassy</td>
</tr>
<tr>
<td>3.11</td>
<td>Rubberised Hair</td>
<td>Embassy</td>
</tr>
<tr>
<td>3.12</td>
<td>Non fire Retarded Foam</td>
<td>Rothmans</td>
</tr>
</tbody>
</table>

Note: Geometry Type 1 Used (Figure 45(a)), In Still Air.
TABLE 25(d): Smoldering Tests Comparing Covered Fillers

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Filler</th>
<th>Fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.13</td>
<td>Non fire retarded Foam</td>
<td>Wool</td>
</tr>
<tr>
<td>3.14</td>
<td>&quot;</td>
<td>Cotton-acrylic</td>
</tr>
<tr>
<td>3.15</td>
<td>Fire retarded Foam</td>
<td>Wool</td>
</tr>
<tr>
<td>3.16</td>
<td>&quot;</td>
<td>Cotton-acrylic</td>
</tr>
<tr>
<td>3.17</td>
<td>High resilience Foam</td>
<td>Wool</td>
</tr>
<tr>
<td>3.18</td>
<td>&quot;</td>
<td>Cotton-acrylic</td>
</tr>
<tr>
<td>3.19</td>
<td>&quot;</td>
<td>Wool-rayon</td>
</tr>
<tr>
<td>3.20</td>
<td>Latex Foam</td>
<td>Polyurethane</td>
</tr>
<tr>
<td>3.21</td>
<td>&quot;</td>
<td>Wool</td>
</tr>
<tr>
<td>3.22</td>
<td>&quot;</td>
<td>Cotton-acrylic</td>
</tr>
<tr>
<td>3.23</td>
<td>Rubberised Hair</td>
<td>Wool</td>
</tr>
<tr>
<td>3.24</td>
<td>&quot;</td>
<td>Cotton-acrylic</td>
</tr>
</tbody>
</table>

Notes: 1) Geometry type 1 used (Figure 45(a)), with Embassy, In Still Air.

TABLE 25(e): Smolder Carried Out in Moving Air

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Direction of Air Flow</th>
<th>Air Flow-Uncorrected (cc/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.25</td>
<td>Against Burn in Cigarette</td>
<td>500</td>
</tr>
<tr>
<td>3.26</td>
<td>&quot;</td>
<td>1000</td>
</tr>
<tr>
<td>3.27</td>
<td>&quot;</td>
<td>1500</td>
</tr>
<tr>
<td>3.28</td>
<td>&quot;</td>
<td>2000</td>
</tr>
<tr>
<td>3.29</td>
<td>&quot;</td>
<td>1150*</td>
</tr>
<tr>
<td>3.30</td>
<td>With Burn in Cigarette</td>
<td>1000</td>
</tr>
<tr>
<td>3.31</td>
<td>&quot;</td>
<td>2000</td>
</tr>
<tr>
<td>3.32</td>
<td>Down at Right Angles</td>
<td>500</td>
</tr>
<tr>
<td>3.33</td>
<td>&quot;</td>
<td>1000</td>
</tr>
<tr>
<td>3.34</td>
<td>&quot;</td>
<td>2000</td>
</tr>
</tbody>
</table>

* As check on theory.

Note: Test carried out with Uncovered non fire retarded foam on Type 1 Geometry, Using Embassy Cigarettes (see Figure 45(c)).

Notes on Tests:

For a type 1 geometry, two 7.5 x 202 cm3 specimens were used one of which had been cut equally in half. This structure allowed the three point contact between the cigarette and filler to be made. In these tests the flexible thermocouple connected to a 'Comark' electronic thermometer was used as the major means of monitoring fire.
FIG. 46: LOCATION OF FLEXIBLE THERMOCOUPLE IN A TYPE 1 SAMPLE.

FIG. 47: LOCATION OF A CIGARETTE IN A TYPE 1 SAMPLE.
Initially the probe was inserted vertically through the bottom of the base piece, to a point approximately 2cm from the surface, so that the thermocouple would not have an influence on the burn. Since there was difficulty in accurately locating the thermocouple and also as the non-fire retarded foam sample hardly burnt (giving insulation to the thermocouple from the heat) there was little sensitivity of temperature recording. The solution to these problems was to insert the thermocouple through the sample until it was flush with the top surface of the base piece. (This is shown in Figure 46).

This form was used with type 3 geometry without additional foam. With a fabric covering, the thermocouple was set so that it was just visible between the weave of the cloth.

The cigarette was accurately positioned in the following manner:

(i) a line was drawn about the circumference (ie. on the paper) half way along the length of tobacco. It was assumed the filter tip would not readily contribute to the fire and, in fact, this was proved to be true since the tip only burnt in the worst fires, when it had relatively little fire contribution

(ii) all samples were weighed

(iii) the flexible thermocouple was inserted through the base piece of filler, and one half of the top piece was placed in position half the diameter of the cigarette from the thermocouple (see Figure 47). Ambient temperature was noted

(iv) the cigarette was lit and quickly placed on top of the base piece, so that the line drawn rested on the thermocouple with the filter-tip facing the observer. A stopwatch was started at this point. The third piece was quickly placed parallel and in contact
FIG 48: MODE OF FABRIC COVERING FOR A TYPE 1 SAMPLE FOR SMOLDERING TESTS.

FIG 49: TYPE 2 GEOMETRY FOR SMOLDER TEST.

(a) Completely Enclosed

(b) Problem of Non-symmetric Crap Around Cigarette

(c) Location of Cigarette Used in Type 2 Smolder Tests
with the cigarette. The chamber door was carefully closed 
(v) the temperature was recorded at convenient times, and any 
necessary observations made. The test was continued until the 
temperature recorded neared room temperature again. Samples were 
examined and reweighed. All tests were duplicated.

In covering the samples with fabric, only the qualitative effect of 
the fabric on the filler was examined, and no attempt was made to 
use realistic ratios of fabrics to filler. 'Sleeves' were made to 
a reasonably tight fit over four sides of the filler (ie. without 
deforming the filler or having loose cloth). (See Figure 48).

In assessing the burn in a type 2 geometry, only uncovered non-fire 
retarded foam was used, in the form of two 7.5 x 200 cm³ pieces, one 
resting on top of the other. With the first run of the type 2 geometry 
a slot was cut in both contact faces, large enough to insert a 
cigarette and therefore enabling complete isolation of the cigarette. 
(See Figure 49(a)). This prevented a large uneven air gap around the 
cigarette (See Figure 49(b)).

It was thought from the type 1 geometry burn that air would be supplied 
from the filler, but this was not the case and therefore it was modified 
by cutting a slot only in the base piece (See Figure 49(c)).

In deciding which geometries should be used, configurations which 
would probable occur in real life were considered of most importance, 
namely:

(i) the situation where a lighted cigarette had rolled down the back 
of a cushion seat and, therefore, in contact with three surfaces
FIG. 50: POSSIBLE POSITIONS CIGARETTES MIGHT ROLL IN AN EASY-CHAIR.
This is paralleled by geometry type 1 (ii) the situation where a lighted cigarette had rolled down the back and under the cushioned seat to be sandwiched between two horizontal surfaces (see Figure 50(b)). This was paralleled by geometry type 2 (iii) the situation where a lighted cigarette was simply resting on the top of and in contact with a horizontal surface. This was paralleled in geometry type 3.

In the bulk of tests, geometry type 1 was used. It proved to be the most dangerous configuration in that it provided the best burn. This was probably due to the three point contact and reasonable ingress of air.

Under the still air conditions of test, the non fire retarded foam proved surprisingly reluctant to reach a state of self-supporting pyrolysis. It was thought that in draught conditions, pyrolysis might be induced and this suggested that test runs in which air could be blown directly on to the cigarette should be investigated since a test should give rise to the following phenomena:

(a) dispersing of local smothing fumes

(b) increase in ignition fuel supply and possibly the temperature at the centre of the fire.

Therefore a copper tube was connected to the gas line at the floor of the chamber and shaped into any of the three suitable positions about the sample. These are shown in Figure 45(c). Air was fed into the tube at various flow rates.

As a check on the burn characteristics of the cigarettes, the Rothmans and Embassy cigarettes were burnt, out of contact with any materials,
Figure 51: Set-up used to measure smolder temperature of a cigarette.
FIG. 52: AMINCO - NBS
SMOKE CHAMBER.

(a) Exterior View.

(b) Details Of Specimen Holder And Pilot Burner

(c) Furnace Support.
but in contact with the thermocouples (see Figure 51). The results of these tests are shown in the Appendix 1.3.

9.4 Small Scale Tests

To complete the inspection of the fabrics and fillers, the fire properties of each were determined by employing some standard small-scale fire tests. The tests tended to be fairly simply in respect to the basic requirements of test samples and equipment, but were fairly strict in establishing "pass" or "fail" values for the materials. The tests described below are commonly found in quality control laboratories, including:

(a) smoke determination test
(b) vertical flammability test
(c) horizontal flammability test
(d) 45° inclined flammability (or alcohol-cup) test
(e) critical oxygen index test.

However, non-composites (i.e. single items) only can be tested. In the first four tests, the apparatus and tough arbitrary standards used by British Aircraft Corporation (Weybridge), were used to evaluate the materials. All samples were pre-conditioned at 21 ± 2°C and 50 ± 5% relative humidity for at least 24 hours before test.

9.4.1. Smoke Evolution

An 'AMINCO NBS' smoke chamber was used to determine the smoke evolution of all the materials. A full description of the apparatus along with its calibration was found in the manufacturer's handbook (85). Figure 52(a) shows an external view of the apparatus. Figure 52(c) shows the furnace assembly and Figure 52(b) shows the details of the specimen holder and pilot burner. Two modes of test were used to estimate smoke produced from a material, namely that under "flaming conditions" and that under "radiant conditions".
(i) Method of Determining Smoke Under Flaming Conditions

The apparatus was turned on, the radiant heater calibrated to give a heat flux of 2.5 watts/sq.cm to fall on the exposed face of the sample, and the pilot burner was bolted on to the gas line. Propane and air (at the ratio of 50:500cc/min propane to air with a calorific values of 350 British Thermal units/hour) were supplied to the burner where the fuel was ignited. The photodetector unit was calibrated.

The preconditioned material was cut to a 3 inch square, backed with aluminium foil (one thousandth of an inch thick) and placed into the sample holder. The sample was then located properly in front of the radiant heater and pilot burner; the test was now underway. The chamber door was quickly shut and the chart recorder (connected to the photodetector amplifier) turned on. The test was run until a peak value of smoke was recorded. Then the chart recorder was stopped, the chamber cleared of smoke and finally the burnt sample was removed. Three samples of each material were tested with single thicknesses of the cloth and filler cut to half inch thickness being used.

From the recorder (plotting time versus neutral optical density equivalents of smoke) the following values were calculated and averages for each material:

(a) $D_{\text{max}}$, the maximum specific optical density
(b) $T_{\text{max}}$, the time to $D_{\text{max}}$
(c) $T_{90}$, the time to a 90 per cent value of $D_{\text{max}}$
(d) $E_{m}$, maximum rate of smoke evolved over any two-minute period of the test
(e) specific optical density values at 1, 2, 3, 4, and 5 minutes (e.g. $D_{S1}$, $D_{S2}$, etc).

In addition weight loss was recorded. At present British Aircraft Corporation use pass criteria of specific optical density $\leq 100$ at 199
FIG 53: F.A.A. VERTICAL STRIP-FLAMMABILITY TEST APPARATUS.
FIG 53: (cont).

(b) Internal View

[Diagram of internal view of a mechanical component, showing various dimensions and parts such as (12) DIA, 15 HOLES, and 3/8 DIA. ROD.]

[Explanation of parts and dimensions, including: "3/8 DIA. ROD," "1/2 DIA. HOLE," "1/2 DIA. 31 HOLES BOTH SIDES," "3/8 DIA. ROD," and "1/2 DIA. 30 HOLES BOTH SIDES." ]

[Additional diagrams showing top view, section through, and view on 1/8 scale, with dimensions and annotations.]
one minute, and <200 at two minutes, these figures being based on the time required for conscious passengers to escape from a burning plane.

(ii) Method for Determining Smoke Under Smoldering Conditions

This method varied from the one above in that the pilot burner was not used to ignite the flammable gas generated from the heated sample; otherwise the test was identical.

9.4.2. Vertical Flammability Test

A strip of material was held rigidly in a vertical position, and a lighted gas flame held to its lower edge; the extent of the fire damage and spread was then determined. A severe variation of the method was selected, based on the Federal Aviation Authority’s test FS 191 Method 5903-1. Figure 53(a) shows the rig, along with the essential parts (Figure 53(b)).

The method of test was basically as follows, the preconditioned material was cut to a 12" x 3" size specimen which was clamped into the sample holder and positioned vertically inside the chamber. The burner was swivelled away from under the hanging sample and lit. The fuel used was Matheson B gas (ex British Oxygen Company) without any air supply passing through a tube (internal diameter of \( \frac{3}{8} \)") at a pressure of 5.0 inches of mercury and flow rate of 420cc/minute; under airless conditions the gas tube has the composition:

- Ethane : \( 3 \pm 1\% \)
- Carbon Monoxide : \( 18 \pm 1\% \)
- Methane : \( 24 \pm 1\% \)
- Hydrogen : \( 55 \pm 1\% \)

With the flame lit and adjusted to a height of 1.5 inches, the minimum flame temperature was 845°C (ie. at flame centre), with a calorific

202
FIG 54: WARP & WEFT DIAGRAM.
value of 539 British thermal units/cubic foot. The door of the chamber was shut (so that the test was carried out in still air conditions), and the burner swivelled back under the sample. The top of the burner was centrally \( \frac{1}{3} \) inch under the lower edge of the sample. In grading the flammability of the material, two standards were used based on flame exposure times of 12 and 60 seconds (with increasing severity of test). Since the flame spread in all the fabrics was very rapid, the shorter exposure was used. Only the fabrics (three samples of each) were tested. The woven fabrics were tested in both warp and weft directions (see Figure 54).

The following parameters were then determined:

(a) char height
(b) char width
(c) time of after flame (ie. time the sample was alight after the burner was removed)
(d) time of afterglow (ie. time the sample smoldered, with glow after the burner was removed)
(e) burning drip time (ie. time burning drips stayed alight after falling from the sample)
(f) weight loss.

As a comparison, the accepted criteria for this method falls into two grades of pass:

GRADE 1 \((V_1)\):
(a) burner alight for 60 seconds
(b) burn length 6\" (152mm) maximum
(c) after-flame time of 15 seconds maximum
(d) time of burning drops, maximum of 3 seconds,

GRADE 2 \((V_2)\):
(a) burner alight for 12 seconds
(b) burn length 8\" (203mm) maximum
FIG 55: C.A.A HORIZONTAL FLAMMABILITY RIG.
(c) after-flame time of 15 seconds maximum
(d) time of burning drops, maximum of 5 seconds.

To pass, the material had to meet each value.

9.4.3. Horizontal Flammability Test

A strip of material was held rigid in a horizontal position, and a lighted burner was held to one end, the extent of fire damage and rate of spread were then determined. The Federal Aviation Authority's test FS 191 Method 5906 was selected as a severe method. Figure 55 shows the rig used including the positions of sample and burner.

The method was essentially as follows:

The preconditioned material was cut to a 12\(\frac{1}{2}\) inches x 4\(\frac{1}{2}\) inches sample, and 1\(\frac{1}{2}\) inches from one end a line was drawn across the width of the upper surface. Another line was drawn 10 inches from this along the length of the sample. The sample was then clamped into the holder (and where necessary the top surface of the fabric, face down). A burner was fed with Matheson B gas to give a flame height of 1.5 inches (the top of the flame being 0.75 inch above the base of the sample) and this was ignited. The sample was then run into the draught free chamber, along a slot so that one of the short edges of the sample was half in the flame. The sample was exposed to the flame for 15 seconds. The resulting flame in the sample was followed and when it reached the 1.5 inches mark, a stopwatch was turned on so that flame spread between the two marks could be estimated.

Three samples of each fabric were tested, including checks, for differences in warp and weft directions where necessary. The following were then determined:
FIG 56: INCLINED FLAMMABILITY TEST RIG.
(a) time alight after the burner was removed
(b) time to burn across the 10 inches section
(c) rate of flame spread over the 10 inches section
(d) distance burnt beyond first mark, if flame became extinguished before reaching the 10 inches mark
(e) weight loss.

The British Aircraft Corporation criteria for this method is as follows:
GRADE 3 (H₃):
Maximum flame spread of 63mm/min (2.5 inches/minute),
GRADE 4 (H₄):
Maximum flame spread of 102mm/minute (4 inches/minute).

9.4.4. 45° Inclined Plane Flammability or Alcohol Cup Test
A material was held rigidly at an angle of 45°, and an alcohol flame was held under it; the extent of fire damage and spread were then determined. The method selected was based on the Civil Aviation Authority's method BL/10-2. The apparatus with the sample and alcohol cup in position is shown in Figure 56.

The method of test was as follows:
The preconditioned material was cut to an 11 inches x 7.5 inches sample, and clamped into the sample holder (the top surface of the fabric face down). The sample was then located in the frame so that the eventual position of the flame on the base of the sample could be ascertained. The sample was removed so that this position could be marked on it by a line across its width, and another line was marked parallel to this 3 inches above it. The alcohol cup was filled with 0.3ml of methylated spirits (0.P.70). The sample was then placed back into position, and
FIG 57: ASTM D2863 CRITICAL OXYGEN INDEX TEST APPARATUS.
the apparatus placed into a draught free chamber. The alcohol was ignited and the following was then determined:

(a) char height, above the lower line
(b) char width, across the upper line
(c) afterglow
(d) burn-through time
(e) burning droplet time
(f) weight loss.

The British Aircraft Corporation acceptance criteria of this method is as follows:

(a) extinction of flame and afterglow within 15 seconds of the alcohol flame being out
(b) char height of 5 inches maximum
(c) char width of 2 inches maximum.

Only three samples of each fabric were tested, including checks for differences in warp and weft directions where necessary.

9.4.5. Critical Oxygen Index Test

British Rail Technical Centre (Derby) kindly carried out all sample preparation, conditioning, testing and calculation of critical oxygen index values for the materials supplied.

The method used was based on ASTM method D 2863 - 70. Essentially, the method called for a thin strip of material to be held vertically in a stream of nitrogen and oxygen. The sample was ignited in an oxygen rich atmosphere, and its concentration was progressively reduced until the flame was just supported in the sample. The percentage of oxygen in the atmosphere at this point was taken as the critical oxygen index value. The apparatus is shown in Figure 57.
All the results for these small scale tests are given in Appendix 1.4.

9.5. Differential Thermal Analysis and Thermogravimetric Analysis

As a final evaluation of the thermal properties of the materials previously tested at full, mid and small scale fire test levels, the value of differential thermal analysis and thermogravimetric analysis for establishing relevant thermal properties were investigated. Other work employing the thermal analysis of polymers has been on relatively simple species, but here the materials are far more complex (see Chapter 6.1). It was suspected that this analysis would produce complex thermograms, and would give a limited (and hence a simple) idea of the thermal stability of the materials.

In these experiments a 'Dupont' Thermal Analyser was used with a 900 Series differential scan calorimetric cell for the differential thermal analysis work, or a 950 Series thermogravimetric analyser for the thermogravimetric analysis work. Setting up procedures were followed from the handbooks supplied by the manufacturer (86, 87 respectively). The following Table 26 shows the range of tests carried out.
TABLE 26

<table>
<thead>
<tr>
<th>Material</th>
<th>DTA N₂</th>
<th>TGA N₂</th>
<th>AIR</th>
<th>AIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere in Cell:</td>
<td>N₂</td>
<td>N₂</td>
<td>AIR</td>
<td>AIR</td>
</tr>
<tr>
<td>Heating Rate (°C/min):</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Temperature (°C):</td>
<td>Inc.</td>
<td>Inc.</td>
<td>Inc.</td>
<td>Inc.</td>
</tr>
<tr>
<td>FR</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>NFR</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>NFR*</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>FR</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>HR</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>L</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>RH</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>W</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>C/A</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>W/R</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>PU</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>PVC</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>Nomex + NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
</tr>
</tbody>
</table>

Key - NT: Not Tested, ✓: Tested, Inc: Increasing

Flow Rate of gas through cell was 400cc/minute in TGA work and 100cc/minute in DTA work.

* Second batch of non fire retarded foam used as check

+ "Nomex" film (0.2mm thickness) ex Dupont used in comparison to the other materials, being one of the so-called "high temperature polymers".

In the differential thermal analysis of the fillers (and of the fabrics to a lesser extent) the following problems arose:

(a) the low density of the foam restricted the quantity of sample that could be used, and therefore major transitions were small and minor ones were lost.

(b) in heating the sample pan packed with foam in the Series 900 cell, the foam expanded forcing the lid off the pan.

As a result erroneous data was displayed on the thermograms, confusing an already complex set of data.

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(c) the thermograms were complicated by the complex nature of the materials, since transitions might have been due to a number of species in the "polymer".

The temperatures at which major weight losses, along with the percentage weight losses were determined from the thermogravimetric analysis thermograms. The isothermal-gravimetric analysis was used to estimate the relative stability of the materials at 200 and 300°C. Typical thermograms are shown in Appendix 2.4, and results are given in Appendix 1.5.
CHAPTER 10 : DISCUSSION OF RESULTS
10.1 Mid-scale Fire Testing

To reiterate, the overall plans and requirements of this work using the redesigned chamber were as follows:

(a) to discover suitable ignition systems and devise suitable sample holders

(b) to develop methods of fire testing non-metallics, and in particular domestic furnishing composites

(c) to produce reproducible and realistic results from which the chamber could be considered a reasonable substitute for full-scale tests.

10.1.1 Burner Redesign

As suggested in Chapter 7.4, it was felt that in using a gas flame ignition source, a particular design of burner was required. Since these burner checks were carried out during the period of rebuilding of the monitoring equipment, results were limited to observations made at the time of burn.

The main point to arise is that a burner (or burners) must be designed to meet sample geometry variation, but at some stage complexity in geometry will prohibit the employment of a burner. At the same time when considering the use of a burner, it must be remembered that relatively few domestic fires have been initiated by hot gas flames, but rather cigarettes, matches or burning newspaper. These sources will be in contact with the material for some time, and can move in contact with the material as it burns away; for the composites tested here this mode of ignition is very likely to occur in real life. Meanwhile the fixed hot gas flame will very rapidly combust the foam and within seconds it burns away from the flame. It is probable that only brief contact with the gas flame is enough to cause self-ignition
in part of a polyurethane sample, however in the three tests carried out here burnt foam remained. This fact suggested that either the multi-source burner used was still too simple, not allowing a large enough initial contact area of flame on foam, or it was not positioned correctly to produce maximum fire spread (and hence a good burn).

The examination of burner design was limited to the work done up to this stage, since it was thought further redesign and construction of a burner would produce an instrument that would really limit the flexibility of the tests. At the same time, it was possible that the sample geometry was too simple, (especially in comparison with actual pieces of furniture). It was expected thinner cross-section and greater surface areas initially exposed to flame (particularly vertical face) would aid fire spread.

Conditions to produce the best fire spread and burn were being sought in these tests. It was hoped in pin-pointing these conditions, that they might be avoided in the design of furnishings. If the chamber could do this, then at least it could take its place amongst those useful tests available for fire investigation.

10.1.2. Morphological Studies

10.1.2.1. Comparison of Ignition Sources in Multipiece Samples

It was immediately noted that in comparison with gas flame ignition, fire initiation in the test piece was slower with the newspaper or match ignition source. This was due to the flame source being lower, and in the case of paper, there first had to be spread of flame through the paper, before heat or flame reached the foam.

The lighted newspaper in 1c or 3c geometries, promoted the highest and greater rates of increase in temperature, smoke toxic gases and weight loss with non fire retarded foam. Surprisingly, employing a
Fig. 5.8: Typical burn patterns found with multi-piece samples.
FIG 58 (cont.):

(a) Two Balls Of Paper Positioned In Geometry 1

(b) Middle Of Back Face Of Geometry 38

(c) A Corner Of Back Side Faces Of Geometry 38

(i.e. symmetrical corner burn)
crumpled semi-spherical ball of newspaper gave remarkably repeatable data in the experiments.

10.1.2.2. Comparison of Ignition Source Position

The relative effect of siting the burning newspaper in the sample geometries is shown in Figure 58(a) to (f). As might be expected the order of fire spread in all cases was as follows:

(a) vertically upwards
(b) across vertical face
(c) across horizontal base
(d) through side wall
(e) through base piece.

In all cases siting the ignition sources symmetrically in the sample and against a vertical face produced:

(a) the greater coverage of flame in the sample, and therefore
(b) the greater temperature increases
(c) the higher temperatures
(d) the higher carbon monoxide concentrations,

while asymmetrical positioning produced:

(a) higher rates of smoke production
(b) higher nitrogen oxides concentrations,

implying that there was a pyrolysis effect in the latter (i.e. radiant heating rather than flame ignition).

In comparing the 1c geometry with either 3b or 2c, the former was found to give the more rapid heat rise, higher gas and smoke concentrations, but the latter were alight for a longer period. The 1c was chosen because the bulk of foam was involved in the fire at an earlier stage.

The single ignition source placed at the base of the back wall produced the best fire, however foam was left at the other end of the sample.
**FIG 59:** MINIMUM SURFACE AREA CHAR PATTERNS.

**FIG 60:** MAXIMUM VERTICAL SURFACE AREA FIRE SPREAD PATTERN.
(ie. the side walls and base ends). See Figure 58(a) to (c).

Figure 58(a) shows the result of burn test ref. 2.7, with paper at the bottom of each side wall, and was the best fire with the greatest weight loss for a 1c geometry.

These tests were perplexing in that at the height of a fire, though flames were large (two or three times the height of the sample, and relatively greater than those observed in the preliminary tests), considerable heat was lost in raising the temperature of the atmosphere. Temperatures at thermocouple TCl were at least 450°C within 90 seconds, and even 600°C was recorded. The thermocouple TCl appears to be equivalent to a ceiling thermocouple immediately above the test piece in a full scale test. The times for which thermocouple TCl temperature remained above 200°C were all greater than 90 seconds. Weight loss was over 55% but again oily residues were present on the floor of the chamber (ie. a few centimetres below the fire centre). In comparison to the preliminary tests all toxic gas levels are lower for non fire retarded foam, reflecting the increased rate of fire spread and hence oxidative combustion. In all cases the sample holder had foam left in corners and along edges after the fire, either due to the 'Meccano' steel frame absorbing heat preferentially, or masking the fire from the foam.

10.1.2.3. Comparison of the Other Sample Geometries

In addition to comparing 1c with 3b and 3c geometries, the examination of possible geometrical extremes was carried out. The compact form of the cube burnt at either side or an top gave overall low fire parameters (see Figure 59 for burn patterns).

At perhaps the opposite end of the geometry spectrum, test pieces 2.11, 2.12 and 2.13 gave very rapid vertical fire spread, in fact it was too fast to follow moving across 10cm gauge marks drawn on the samples.
FIG. 61: COMPARISON OF BURN PATTERNS IN FREELY HANGING AND CLAMPED VERTICAL FLAMMABILITY SAMPLES.
Samples 2.12 and 2.13 collapsed to the floor of the chamber at an early stage, therefore no longer maintaining the desired and crucial profile to the fire, and continued to burn in this unwanted orientation, (i.e. crumpled heap). The problem with these types of geometry was obtaining stability during the length of the test. The typical spread occurred as shown in Figure 60.

This pattern showed fire spread was greatest over the surface of specimen and at the thinnest section (i.e. width). Comparison made with the burn pattern observation in the vertical flammability test sample (see Figure 61), shows that the sample holder restricted the fire spread and indicated the artificial nature of this test. For 2.11, 2.12 and 2.13 geometries the monitoring arrangements in the chamber were totally inadequate due to the "unrealistic" shapes of sample.

The 7.5 x $20^2$cm$^3$ geometry (i.e. paper on top surface) burnt in test 2.10 producing slightly lower temperatures than the multipiece samples, and it burnt more slowly, partly because of oil build-up, with reductions in toxic gases and smoke levels. The geometry in test 2.26 (vertical, with paper underneath) produced a very good burn (this is discussed below).

10.1.2.4 Special Modifications to the Rig

(i) Wooden Sample Holder.

When using the wooden sample holder the overall burn was slightly improved with the edge effect being reduced, but still the slats
effected the burn in the corners (i.e. there was shielding by the frame). Surprisingly, even though the frame was completely enveloped in flame, the wood was not even charred; this again indicates very great heat loss from the seat of combustion.

(ii) False Ceiling

The dimensional ratio of the chamber (approximately 1 : 1 : 1) is not really related to that of a typical living room (8 ± 2 : 14 ± 3 : 12 ± 2), where in a fire the ceiling may be in contact with flame and could influence reheating of the fire site (i.e. by downward reflection). The large flames produced, acting as the vehicle for most of the heat loss from the fire site, suggested the need for a lower ceiling in the chamber. At both heights (i.e. 30 and 40cm investigated for a false ceiling), little improvement resulted, the flame moving away sideways. The use of reflective foil on the ceiling, however, changed the picture completely. The increase in the rate of temperature was the highest recorded and at thermocouple TC1 the maximum was 630°C. Smoke build up was rapid (here related to fast burn rate, rather than smoldering). As the oil residues were minimal the weight loss (i.e. 70%) may be attributed to conversion to gases and vapours. Carbon monoxide was at high, at dangerous for short exposure concentrations, again showing effect of burning off the oil produced. Hydrogen cyanide was also slightly up but nitrogen oxides down.

These tests indicated that the ceiling can have a varying degree of effect on the fire beneath, but having reflective coverings (even though the best burn was achieved under such circumstances) increased the artificiality of the test.

10.1.3. Comparison of Fabric Covered Non-fire Retarded Foam

In the first two tests (i.e. 2.20, 2.21) using fabric covered non-fire retarded foam there was preferential fire spread into the foam.
unprotected by glasscloth) rather than the fabric covered part (especially cotton-acrylic covered non fire retarded foam). This led to the use of glasscloth as explained in the experimental work. The overall effect of the fabrics on non fire retarded foam in fire spread is much the same as found in the preliminary work (see Chapter 7.4) as shown in Table 27.

**TABLE 27**

<table>
<thead>
<tr>
<th>Property</th>
<th>Descending Order (from greatest to lowest)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Spread</td>
<td>C/A PU W/R W</td>
</tr>
<tr>
<td>Maximum Rate of</td>
<td>C/A W PU W/R</td>
</tr>
<tr>
<td>Temperature Increase</td>
<td>C/A W/R W</td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>PU W/R C/A</td>
</tr>
<tr>
<td>Weight Loss</td>
<td>PU W/R C/A</td>
</tr>
<tr>
<td>Smoke</td>
<td>W PU W/R C/A</td>
</tr>
<tr>
<td>Toxic Gases</td>
<td>PU W/R C/A</td>
</tr>
</tbody>
</table>

Note: * wool smoldered and intumesced with a small flame producing more smoke earlier than the cotton-acrylic which burnt with a large flame. PVC was not used in these tests.

All compositions burnt with a maximum temperature well over 450°C and smoke levels > 2 neutral optical density in less than 3 minutes. Carbon monoxide produced by polyurethane fabric covered non fire retarded foam was above dangerous for short exposure concentrations, as were levels of nitrogen oxides for cotton-acrylic and wool-rayon. Only hydrogen cyanide concentrations were below the findings of the preliminary tests, indicating a more oxidative combustion. It was thought that the glasscloth protection, covering most of the sample, might have too much influence on the fire spread particularly in the later stages of the test.
A theory of heat loss was developed whilst observing test involving 1c geometry. Fire, in moving through the thickness of foams (uncovered), initially produces, as might be expected, a heat front which moved ahead of the flame, to pyrolyse the foam to gas and smoke. This appeared to partly escape through the open cell structure of the foam to the air, away from the naked flame. This air moving in thermal currents reached a point above the test piece, where the flammable gases were flashed off without contributing to the burn in the sample. This was also observed in covered non fire retarded foam, where the foam protected from flame by the glasscloth, was heated to produce fumes. These fumes, protected by the glasscloth passed up between cloth and foam, and eventually out into the atmosphere where they were occasionally ignited and appeared as small flashes of flame. This suggested the theory that there is a critical thickness of foam, or alternatively, certain types of woven cloth, which permitted pyrolysed gases to escape the effects of the flame of the fire. In these circumstances flash fires above the fire site, or more smoke or abnormal concentrations of gases might all be observed. Ideally, to lower flammability in furnishings, low thicknesses of foam and the use of certain cloths should be avoided.

There is some sign that the thickness of foam chosen (ie. 2.5cm) produced, accidentally, very open "chair-like" geometries, which permitted heat to escape fairly easily. It may be still feasible that precise scaling down of the chair(s) used in the tests of the Inter-Company Urethane Panel might have achieved fuller, better and more significant burns.

10.1.4. Comparison of Single-piece Samples

The main problems in using the 1c Geometry of sample were:
(a) heat loss
(b) difficult construction
(c) limited range of sample orientation
(d) limited supply of non fire retarded foam at that thickness, and therefore tests employing \(7.5 \times 20^2 \text{cm}^3\) samples were continued since:

(a) reduced surface area (for better fabric coverage)
(b) there was a desire to repeat some of the initial work with a more rigorously controlled rig
(c) they were readily available.

In this series of tests there was also an opportunity to simulate the effect of positioning the ignition source in the various parts of the chair, i.e.

(a) against the base of the vertical piece
(b) on top of the horizontal piece
(c) under the horizontal piece

(i) Comparison of Uncovered Fillers

The general comments made in Chapter 7.4 on the preliminary test results, comparing the uncovered fillers is equally relevant here. With the vastly improved monitoring of fire parameters, the graphs generated revealed greater detail on how the fire proceeded.

Table 28 summarised the relative fire danger of the filler.
<table>
<thead>
<tr>
<th>Property</th>
<th>Decreasing Order of Danger</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of Temperature Increase</td>
<td>RH HR W E L FR</td>
<td>The structure of the rubberised hair allowed the greatest ease in fire spread while flames from fire retarded foam hardly effected TCI.</td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>NFR W E HR RH FR</td>
<td>Non fire retarded high resilience and latex foams all contributed the highest heat release. All except fire retarded foam, were above 460°C.</td>
</tr>
<tr>
<td>Weight Loss</td>
<td>RH NFR HR L FR</td>
<td>Non fire retarded, high resilience and latex foams lost the same mass of material in the fire, but percentage losses were 75, 75 and 25% respectively. They were 100% for rubberised hair and 25% for fire retarded foam.</td>
</tr>
<tr>
<td>Time Above 200°C (for TCI)</td>
<td>NFR L HR RH FR</td>
<td>All apart from fire retarded foam, were above 200°C for more than 90 seconds.</td>
</tr>
<tr>
<td>Time to Maximum Smoke Level</td>
<td>L RH FR HR NFR</td>
<td>The polyurethanes reflect their fire retardancy properties.</td>
</tr>
<tr>
<td>Rate of Smoke Increase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Carbon Monoxide</td>
<td>L NFR RH FR HR</td>
<td>Latex produced the dangerous for short exposure concentrations.</td>
</tr>
<tr>
<td>Maximum Hydrogen Cyanide</td>
<td>RH FR NFR HR L</td>
<td>All produced levels well below the dangerous for short exposure concentrations</td>
</tr>
<tr>
<td>Maximum Nitrogen Oxides</td>
<td>NFR RH FR HR L</td>
<td>Non fire retarded foam and rubberised hair produced levels above the dangerous for short exposure concentrations</td>
</tr>
</tbody>
</table>
FIG. 62: BURN PATTERNS RESULTING FROM PAPER IGNITION ON VERTICAL PU.S.
The final appearance of the polyurethane were as shown in Figure 62.

In addition latex produced a fused lump, and rubberised hair was burnt to ashes. The polyurethanes burn patterns are better than those observed in the preliminary tests. However, oil residue was in evidence particularly with non fire retarded and high resilience foams. It had been hoped the nearness to the floor and the presence of the ignition source immediately under the sample might have caused oil ignition.

(ii) Comparison of Covered Fillers
(a) in vertical mode.

In this set of tests there was an opportunity to compare fabrics on the 7.5 x 20 cm$^3$ geometry of non fire retarded foam and wool and cotton-acrylic fabric on rubberised hair. The comments made in Chapter 7.4 about the modifying effect a fabric has on a filler also apply here.

Table 29 summarises the fire parameters of the composites in descending order of fire danger.
### TABLE 29

<table>
<thead>
<tr>
<th>Fire Parameter</th>
<th>With NFR</th>
<th>With RH</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of Temperature Increase</td>
<td>PU W/R = PVC W C/A</td>
<td>CA W</td>
<td>Apart from polyurethane, fabrics normally slowed the rate.</td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>PU W W/R PVC C/A</td>
<td>CA W</td>
<td>All above 300°C except cotton acrylic at 235°C but lower than non fire retarded foam alone. On rubberised hair lower, though both above 420°C. All above 75 seconds.</td>
</tr>
<tr>
<td>Time Above 200°C</td>
<td>W PU PVC W/R C/A</td>
<td>C/A W</td>
<td>All lower than non fire retarded foam alone (PVC at 70% the rest at 60%) Slight residue of rubberised hair left when covered.</td>
</tr>
<tr>
<td>% Weight Loss</td>
<td>PVC Rest</td>
<td>W CA</td>
<td>Increase over non fire retarded foam alone. Decrease for rubberised hair.</td>
</tr>
<tr>
<td>Time to NOD &gt; 2</td>
<td>PVC W = PU W/R C/A</td>
<td>W C/A</td>
<td>.undo</td>
</tr>
<tr>
<td>Maximum Rate of Smoke Increase</td>
<td>W PVC W/R C/A</td>
<td>C/A W</td>
<td>Cotton acrylic and wool-rayon were at dangerous for short exposure concentrations and all levels of carbon monoxide were doubled by fabrics. Fabrics reduced carbon monoxide levels for rubberised hair. Increase over uncovered non fire retarded foam, decrease over uncovered rubberised hair, all below the dangerous for short exposure concentrations. Reduction in both cases, indicating a less oxidative fire.</td>
</tr>
<tr>
<td>CO Maximum</td>
<td>C/A W/R W PU = PVC C/A</td>
<td>W C/A</td>
<td></td>
</tr>
<tr>
<td>HCN Maximum</td>
<td>W C/A PVC W/R PU</td>
<td>W C/A</td>
<td></td>
</tr>
<tr>
<td>NOX Maximum</td>
<td>W C/A W/R PU = PVC</td>
<td>C/A W</td>
<td></td>
</tr>
</tbody>
</table>
Additional Comments:

In comparison to the preliminary tests, similar orders of rating were normally found, but toxic gas levels were lower, (even though weight loss was slightly greater). It is possible that the paper igniter was responsible for the difference in slowing initial spread and having a larger and longer contact with the sample, than the gas flame. This demonstrates that small differences in setting up procedures produce some fire parameter variation.

It has been noted in all tests that PVC (and to some extent latex) released a large amount of particulate matter in to the atmosphere, as witnessed by the "soot correction" being higher for this material.

(ii) Horizontal Mode, Ignition source on Top

Observations showed this mode of ignition usually caused the fabrics to catch fire. The rate at which flame acted on the foam was dependent on the ignition and burn through properties of the fabrics. With a relatively slow burn through, a smolder area occurred in the foam, which was soaked with oil, hampering downward fire spread. This effect was observed with wool and wool-rayon fabrics, where little or no fire occurred, and the temperature increase recorded due only to the paper burning.

The other temperature plots (see Appendix 2.2.) indicates the relative fire hindering properties the rest of the fabrics have, in relation to uncovered non fire retarded foam. The uncovered non-fire retarded foam in this mode, in comparison with the vertical geometry, burnt more slowly with relatively lower temperatures. (Note: In the horizontal mode thermocouple TCI is further from the sample).
Table 30 compares the three fabrics on non-fire retarded polyurethane foam with uncovered non-fire retarded foam.

**TABLE 30**

<table>
<thead>
<tr>
<th>Property</th>
<th>Descending Order of Fire Danger</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Temperature</td>
<td>NFR PVC C/A PU</td>
<td>These figures show cotton-acrylic to have the worst horizontal fire resistance of the fabrics tested.</td>
</tr>
<tr>
<td>Maximum Rate of Temperature Increase</td>
<td>PU ≥ C/A NFR ≥ PVC</td>
<td></td>
</tr>
<tr>
<td>Temperature Increase</td>
<td>C/A NFR PVC PU</td>
<td></td>
</tr>
<tr>
<td>Total Burn Time</td>
<td>C/A PU NFR ≥ PVC</td>
<td></td>
</tr>
<tr>
<td>Weight Loss (%)</td>
<td>C/A PU ≥ PVC NFR</td>
<td></td>
</tr>
<tr>
<td>Time to Reach &gt;2 NOE</td>
<td>C/A PU ≥ PVC NFR</td>
<td></td>
</tr>
<tr>
<td>Maximum Carbon Monoxide</td>
<td>PU PVC ≥ NFR C/A</td>
<td>All levels of gases were below the dangerous for short exposure concentration</td>
</tr>
<tr>
<td>Maximum Hydrogen Cyanide</td>
<td>C/A PU PVC NFR</td>
<td></td>
</tr>
<tr>
<td>Maximum Nitrogen Oxides</td>
<td>C/A NFR PU ≥ PVC</td>
<td></td>
</tr>
</tbody>
</table>

(iii) Horizontal mode, ignition source under sample

The samples here had to be supported in a sample holder, and there were resulting "frame effects" observed in the first few burns. Test 2.43 to 2.45 showed the frame was giving too much support and badly impeding fire spread (eg. the opportunity to spread from the base around and up the sides of the sample was considerably hindered and often stopped).

The rest of this series of tests employed the opened frame (comparing wool-rayon fabric in both modes indicated the improvement in burn). All further comments are made with reference to the open frame tests.

The lower temperature profiles indicate the inflexibility problem of the monitoring equipment, since observations showed that for a good part of the burn, the sample shielded the thermocouples from the fire. The glasscloth also inhibited flame spread to the top surface. As a result, temperatures profiles probably do not relate to the full
heat release (if compared with a vertical test piece).

Because of the position of ignition source in reference to the sample, there was a relatively large horizontal cross section of filler. Therefore, light from the fire effected smoke measurement. All smoke traces showed inflections after two minutes (see Appendix 2.2.) when the illuminating power of the fire was greater than that of the sampling light beam. This caused additional light to fall on the sample photodetector. This suggests under certain operational conditions, a brighter optical beam is needed to counteract this effect, since the sample photodetector is otherwise well shielded from stray light.

The fire spread mode was similar to that of the "vertical" geometry samples, namely:

(a) the burning paper ignited the fabric
(b) burn continued up and into the filler, any delay of heating of the filler was related to the flame resistance properties of the fabric
(c) spread to the upper surfaces was dependent on the rate of flame spread on the under-surface of the fabric
(d) the glasscloth did not burn through, showing artificiality in the test.

Some of these points are indicated in Table 31.
<table>
<thead>
<tr>
<th>Property</th>
<th>Descending Order of Fire Danger</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Temperature</td>
<td>NFR PVC W W/R C/A PU</td>
<td>In adding fabric to the non fire retarded foam, resulted in the overall amount of material to be consumed to be greatly increased (with three types of composite losing 90% weight). Cotton-acrylic and polyurethane fabric did not burn through, but remained as charred fibres.</td>
</tr>
<tr>
<td>Maximum Rate of Temperature Increase</td>
<td>NFR PVC W = W/R C/A = PU</td>
<td>The high levels of hydrogen cyanide for the wool must be partly attributed to the chemistry of the fabric, and due to the induced smoldering effects in the case of PVC. The high levels of nitrogen oxides for cotton-acrylic may be due to the ease of burn through. No levels were above the dangerous for short exposure concentrations</td>
</tr>
<tr>
<td>Time TC1 above 200°C</td>
<td>NFR PVC W Rest</td>
<td></td>
</tr>
<tr>
<td>Weight Loss (%)</td>
<td>C/A=PU(100%) W PVC W/R NFR</td>
<td></td>
</tr>
<tr>
<td>Time to NOD=2</td>
<td>PVC W NFR Rest</td>
<td></td>
</tr>
<tr>
<td>Maximum Rate of Smoke Increase</td>
<td>PVC NFR = W C/A = W/R PU</td>
<td></td>
</tr>
<tr>
<td>Maximum Carbon Monoxide</td>
<td>W PVC = W/R = C/A PU NFR</td>
<td></td>
</tr>
<tr>
<td>Maximum Hydrogen Cyanide</td>
<td>W PVC W/R C/A PU NFR</td>
<td></td>
</tr>
<tr>
<td>Maximum Nitrogen Oxides</td>
<td>W C/A W/R PU = PVC NFR</td>
<td></td>
</tr>
</tbody>
</table>
Apart from PVC (with a maximum smoke level of a neutral optical density greater than 2 within 40 seconds, and smoke rate of 8.6 NOD units/minute), smoke levels were similar for those of uncovered non-fire retarded foam. However, carbon monoxide and hydrogen cyanide levels were increased by at least threefold, and all nitrogen oxides levels were slightly increased over those for non-fire retarded foams alone. These probably relate to the greater amount of materials burnt (especially the nitrogen oxides levels), and the pyrolysis effects produced by the addition of the fabrics (especially for the threefold increases of hydrogen cyanide and carbon monoxide).

These tests in particular supported the assumption that the air in the chamber was adequate to support complete combustion of these samples.

The burn tests of burning paper alone, (resting on the floor), show minimal temperature and heat increase, and no measurable levels of smoke or carbon monoxide.

A synopsis of the results is shown in Table 32(a) and (b).
TABLE 32(a) Synopsis of Combustion Tests

<table>
<thead>
<tr>
<th>Composition</th>
<th>Geometry of Sample</th>
<th>Total Burn Time</th>
<th>Weight Loss</th>
<th>Max. Temp</th>
<th>Time to NOD ( \equiv 2.0 )</th>
<th>Max. CO</th>
<th>Max. NO(_x)</th>
<th>Max. HCN</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFR</td>
<td>1c (^+)</td>
<td>**</td>
<td>*</td>
<td>**</td>
<td>***</td>
<td>**</td>
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</tr>
<tr>
<td>NFR-W</td>
<td>&quot;</td>
<td>**</td>
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<td>*</td>
<td>*</td>
</tr>
<tr>
<td>NFR-C/A</td>
<td>&quot;</td>
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<td>*</td>
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</tr>
<tr>
<td>NFR-N/R</td>
<td>&quot;</td>
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<td>*</td>
<td>***</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>NFR-PU</td>
<td>&quot;</td>
<td>**</td>
<td>*</td>
<td>**</td>
<td>***</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>NFR</td>
<td>7.5 ( \times 20\text{cc/Upright}^\circ)</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>***</td>
<td>**</td>
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<td>***</td>
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<tr>
<td>FR</td>
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<td>HR</td>
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</tr>
<tr>
<td>RH</td>
<td>&quot;</td>
<td>**</td>
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<td>**</td>
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<tr>
<td>NFR-N/R</td>
<td>&quot;</td>
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<td>**</td>
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</tr>
<tr>
<td>NFR-PU</td>
<td>&quot;</td>
<td>**</td>
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<td>**</td>
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<td>*</td>
<td>*</td>
</tr>
<tr>
<td>NFR-PVC</td>
<td>&quot;</td>
<td>**</td>
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<tr>
<td>RH-W</td>
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<td>**</td>
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<td>***</td>
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</tr>
<tr>
<td>RH-C/A</td>
<td>&quot;</td>
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<td>***</td>
<td>*</td>
</tr>
</tbody>
</table>

Contd..
<table>
<thead>
<tr>
<th>Composition</th>
<th>Geometry of Sample</th>
<th>Total Burn Time</th>
<th>Weight Loss</th>
<th>Max. Temp</th>
<th>Time to NOD &gt; 2.0</th>
<th>Max. CO</th>
<th>Max. NO&lt;sub&gt;x&lt;/sub&gt;</th>
<th>Max. HCN</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFR</td>
<td>7.5x20²cc/horizontal&lt;sup&gt;++&lt;/sup&gt;</td>
<td>*</td>
<td>**</td>
<td>**</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>NFR-W</td>
<td>&quot; / &quot;</td>
<td>***</td>
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<td>***</td>
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<td>***</td>
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<td>***</td>
</tr>
<tr>
<td>NFR-C/A</td>
<td>&quot; / &quot;</td>
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<td>*</td>
<td>***</td>
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<td>***</td>
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<td>***</td>
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<tr>
<td>NFR-N/R</td>
<td>&quot; / &quot;</td>
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<tr>
<td>NFR-PU</td>
<td>&quot; / &quot;</td>
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<td>***</td>
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<tr>
<td>NFR-PVC</td>
<td>&quot; / &quot;</td>
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<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>NFR</td>
<td>7.5x20²cc/horizontal&lt;sup&gt;⊙&lt;/sup&gt;</td>
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<td>**</td>
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<tr>
<td>NFR-W</td>
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<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>NFR-C/A</td>
<td>&quot; / &quot;</td>
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<td>***</td>
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<tr>
<td>NFR-N/R</td>
<td>&quot; / &quot;</td>
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<td>***</td>
</tr>
<tr>
<td>NFR-PU</td>
<td>&quot; / &quot;</td>
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<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>NFR-PVC</td>
<td>&quot; / &quot;</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

Key:

* Using two pieces of burning A4 paper
** Using one piece of burning A4 paper under base of sample
<sup>++</sup> Using one piece of burning A4 paper on top of sample
<sup>⊙</sup> Using one piece of burning A4 paper under base of sample
<sup>∞</sup> Levels to produce death in less than one hour.
### TABLE 32(b) Effects of Covering Fabric on Filler in Various Geometries

<table>
<thead>
<tr>
<th>Filler in Particular Geometry</th>
<th>Fabric</th>
<th>Max Temp</th>
<th>Time To NOD ≥ 2</th>
<th>Max CO</th>
<th>Max NOₓ</th>
<th>Max HCN</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFR in Upright Geometry</td>
<td>W</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>C/A</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>W/R</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>PU</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>NFR in Upright Geometry</td>
<td>W</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>C/A</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>W/R</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>PU</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>PVC</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>RFI in Horizontal Geometry</td>
<td>W</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>C/A</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>NFR in Horizontal Geometry</td>
<td>W</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>C/A</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>W/R</td>
<td>↓</td>
<td>↑</td>
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<td>↑</td>
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<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>PU</td>
<td>↑</td>
<td>↑</td>
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<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>&quot; &quot; &quot; &quot; &quot;</td>
<td>PVC</td>
<td>↑</td>
<td>↑</td>
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<td>↑</td>
<td>↑</td>
</tr>
</tbody>
</table>

Symbols are the same as those used in Table 28(a)

Trends derived from data in Table 28(a)

Key: 
- ↑ Increase
- ↓ Decrease
- ↔ No change
10.1.5 Cigarette Smoldering Tests

Since some domestic fires are not caused by flaming ignition, this series of tests was initiated to see what the effect of a typical smoldering source was and to check which combination of fillers and fabrics produced fire hazards and possibly flaming conditions.

(i) Cigarette Burns

Graph 1.3.1. in Appendix 2.3 shows the temperature profiles of Embassy and Rothman cigarettes burning in still air. The former produced a maximum of $175^\circ$C after 7.3 minutes, the observed half burn time was 6.5 minutes and full burn time 13.0 minutes, indicating a probable steady rate of tobacco burn. For the latter the maximum was $217^\circ$C after 8.8 minutes, half burn time of 8.5 minutes and full burn time of 17 minutes. It must be remembered these are the temperatures measured at the surface of the cigarette (ie. at the paper covering), this being the usual contact point with the test sample. The centre of the burning cigarette would be hotter.

(ii) Geometric Studies

Test 3.1 using Geometry 1 assessed thermocouple positioning and showed the thermocouple could produce relevant results, without unduly hindering the fire spread action of the cigarette. Luckily the non fire retarded foam only burnt in the immediate vicinity of the cigarette, and what was recorded proved to be the localised temperature increase as the burn spread uniformly along the cigarette to the thermocouple, and then decreased as the burn passed it.

With the thermocouple at 2cm below the surface of the foam, the following effects were noted:

(a) insulation by the foam giving rise to low temperature levels recorded

(b) imprecise location of the thermocouple
FIG. 63: TYPICAL SMOLDER PATTERN IN A TYPE 1 SAMPLE OF UNCOVERED NFR.
(c) no evidence that the cigarette remained balanced above the thermocouple, (this in turn would effect the manner in which the test proceeded).

From this test the char pattern produced in the non fire retarded foam was as shown in Figure 63.

From the burn pattern, dimensions of char were measured as a means of showing the fire spreads, ie.

\[ \begin{align*} 
& a \quad \text{maximum char height} \quad c \quad \text{maximum char width} \\
& b \quad \text{maximum char length} \quad d \quad \text{maximum char depth} 
\end{align*} \]

Test 3.2 with the thermocouple in contact with the lower edge of the cigarette paper and flush with the top surface of the base piece, improved temperature monitoring, and showed that the thermocouple only had limited restrictions on the cigarette in the later stages of a burn. Other burns with any range of foams showed that induced smoldering over-rove any effect the cigarette might have had in its later stages of burn.

Test 3.3, with the cigarette completely surrounded by non fire retarded foam, showed some outside supply of air was required to initiate fire spread in the foam. As it happened, the cigarette was stifled and extinguished within a few minutes of the test starting, having no effect on the foam.

Test 3.4, allowing some ingress of air produced smoldering, and a maximum of 250°C was reached after 27 minutes, although very little foam was burnt away.
Fig. 64: Suggested fire spread pattern with smolder burn.

The Arrows Indicate Spread Which Becomes More Uniform (i.e., spherical) Moving Away From Cigarette.
In Test 3.5, with a cigarette just resting on top of a piece of non fire retarded foam, the burn was very limited. To produce the worst fire parameters, test 3.2 was used as the basis for the other tests.

(iii) Comparison of Uncovered Fillers

In comparison with the combustion tests non fire retarded foam was found to have reversed its relative fire property role with the fire retarded and high resilience foams. Though non fire retarded foam was hardly consumed by the smoldering fire with the pattern shown in Figure 63, fire retarded and high resilience foams were charred to near completion (see Figure 64), with the high resilience being converted into a black carbonised foam. With high resilience and fire retarded foams, three pieces of the test sample fused together, effectively sealing the smolder from any further ingress of air, at a relatively early stage of the burn. This indicated that smolder in these foams was possible with an insufficient air supply from outside, or by air supplied from the cellular structure of the foam. It was noted that the fire in the high resilience and fire retarded foams neared completion and the only apparent reason for the fire ceasing was insufficient fuel (ie. not enough foam). This type of test could have status as a limited full scale test, giving quantitative values of temperature rise and fire spread in the early stages of smolder.

Latex burnt readily under induced smoldering conditions from the expected charred mass, and high levels of smoke. Rubberised hair was hardly effected at all.

The chemistry of the polyurethanes and the latex foams, go some way to explaining their reactions to low temperature smoldering (see Chapter 3.3). In combustion conditions to produce fire, temperatures are well in excess of those needed to just effect hydrogen bonding.
or crystallinity and the fire state is dependent on the overall fire retardency. To some extent thermogravimetric analysis results shows the relative instability of the three polyurethanes. Temperature maximum for the fire retarded foam reached 680°C and for the high resilience foam 460°C, it was impossible to say if fire retarded foam caught alight, with a sudden temperature increase, due to the thick smoke. In duplicate tests temperature traces are very similar.

Latex had a similar thermal instability at low temperatures and readily underwent an autopyrolytic state. Rubberised hair might be expected to have similar properties, but its relative low mass and open structure were little affected by the cigarette. A cigarette had little contact with the fibres in the rubberised hair, those which were burnt could only smolder along the fibre, and heat could be dissipated readily into the air inside the structure of the filler.

Table 33 illustrates the above points.

**TABLE 33: Comparison of the Fillers in Smoldering Test**

<table>
<thead>
<tr>
<th>Property</th>
<th>Order of Decreasing Fire Danger</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Temperature</td>
<td>FR HR L NFR RH</td>
<td>Some oily residue observed after burning the high resilience foam</td>
</tr>
<tr>
<td>Maximum Rate of Temperature Increase</td>
<td>FR L HR NFR RH</td>
<td></td>
</tr>
</tbody>
</table>

The degree of smoldering burn in double the usual volume of high resilience and fire retarded foam, shows that the atmosphere of the chamber, is capable of supplying air at least for these types of tests.

The longer contact time of the Rothman's in the non fire retarded foam only had a slight increase in the overall temperature profile.
(iv) Comparison of Fabric Covering on Fillers.

It must be remembered that the fabrics were used to cover areas of foam well over the ratio derived from full-scale tests. Therefore data generated was only relevant to early stages of burn.

The tests indicated the fabrics have varying degrees of resistance to burn through by a smoldering cigarette, and any fire that resulted was dependent on the fabric. This in particular, is shown by the cotton-acrylic covered non-fire retarded foam composite where a high temperature burn occurred. In this case the cotton-acrylic probably acted as a readily ignitable smoldering source, promoting a higher contact temperature than for the cigarette alone, and high enough to overcome the thermal stability of the non-fire retarded foam. At that stage autopyrolysis took over, and the heat of pyrolysis for the non-fire retarded foam was high enough to maintain the burn.

The woollen covering on otherwise self-smoldering foams had an opposite effect. The cigarette appeared to char, and intumesced fibres exposed which in turn acted as a thermal barrier to any further ingress of heat (i.e. to the foam). As a result char in the wool covered non-fire retarded foam was limited to the immediate area of the cigarette. However, in the tests involving high resilience foam, only wool acted as a fire barrier, wool-rayon, cotton-acrylic and polyurethane fabrics promoted smolder. The rubberised hair covered by either cotton-acrylic or wool did not burn, and again this must be put down to the structure of the rubberised hair. Wool with non-fire retarded foam, wool with high resilience foam, wool with latex, wool with rubberised hair, and cotton-acrylic with rubberised hair composites did not smolder, and their maximum internal temperatures were less than 280°C, releasing no significant levels of carbon monoxide. Cotton-acrylic with non fire
retarded foam, cotton-acrylic with high resilience foam, wool-rayon with high resilience foam, polyurethane fabric with high resilience foam and cotton-acrylic with latex composites did smolder and burn well. The maximum internal temperatures were greater than 450°C, remaining above 200°C for longer than 20 minutes, producing excessive carbon monoxide (greater than the dangerous for short exposure concentrations, apart for high resilience foam covered with wool-rayon). These tests showed high resilience foam combined with certain fabrics was particularly prone to smolder.

Some of this series of tests were fully monitored. High resilience foam covered with wool-rayon produced an atmospheric temperature of 135°C (at thermocouple Tc1) and smoke of neutral optical density > 2.0 in 24 minutes; latex covered with cotton-acrylic also reached smoke of a neutral optical density > 2.0 in 24 minutes. The rest of the fixed thermocouples only reached a few degrees above room temperature, showing the limited heat release into the chamber. Table 34 illustrates some of the points made above.

**TABLE 34**: Comparison of Fabric Covered Fillers in Smoldering Tests

<table>
<thead>
<tr>
<th>Property</th>
<th>Order of Decreasing Fire Danger</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Temperature</td>
<td>C/A-HR C/A-NFR W/R-HR C/A-FR C/A-L PU-HR</td>
<td>Latex smolders at cooler temperatures than the polyurethanes</td>
</tr>
<tr>
<td>Maximum Rate of Temperature Increase</td>
<td>C/A-HR C/A-L C/A-FR Rest</td>
<td></td>
</tr>
<tr>
<td>Weight Loss (%)</td>
<td>C/A-HR W-HR C/A-NFR C/A-L PU-HR Rest</td>
<td></td>
</tr>
<tr>
<td>Maximum Carbon Monoxide</td>
<td>C/A-HR C/A-L PU-HR C/A-NFR C/A-FR W/R-HR Rest</td>
<td></td>
</tr>
</tbody>
</table>

(v) Ventilation Effects

It had been thought that ventilating the area of smolder in the non-fire retarded foam might produce two effects:
(1) A draught in the opposite direction to the slow burn rate in the cigarette, so heat contact at a particular point may be prolonged.

(2) A draught in the direction of burn increasing surface smolder temperature and perhaps overcome the thermal stability of the non fire retarded foam.

(a) Ventilation in the opposite direction to the burn of the cigarette. Although there was some increase of maximum temperatures recorded by increasing ventilation, an autopyrolytic state was not reached. By drawing a graph of maximum temperature (or time to maximum temperature) versus apparent air flow rate, it was shown that the highest maximum temperature might be obtained at 1150cc/minute. Even though an experiment at this rate produced part of what was estimated (i.e. peak temperatures), no autopyrolytic state was reached.

It was shown that above the flow of 1150cc/minute, the cooling effect of the draught became all important.

(b) Ventilation in the direction of burn By increasing ventilation maximum temperature decreased (i.e. from 310 to 228°C, from still moving air at 2000 l/min) and there was an apparent reduction of burn in the foam, while there was an increase rate of cigarette burn (see char dimensions in Appendix 2.3).

(c) Ventilation at right angles to direction of burn. Here, increasing ventilation increased cigarette burn rate. Although there was little effect on maximum temperature (at 295°C), the time to this maximum decreased. Increasing ventilation in this manner is shown to reduce char dimensions.

In conclusion, ventilation is shown to have some effect on a smolder. A flow in the opposite direction of cigarette burn may increase maximum temperature, and this may be significant to push a composite into a smoldering situation, if not already in that state.
A summary of results indicating the various effects of fabric coverings on the fillers is shown in Appendix 2.3.

In the majority of the medium scale tests, smoke levels were in an unmeasurable excess of neutral optical density of 2.0, and along with an oily residue this factor prevented values of mass density being calculated.

10.2 Small Scale Fire Tests

10.2.1. General Comment

As said before, the arbitrary standards set for the small scale fire tests have been laid down by the British Aircraft Corporation from Federal Aviation Authority directions. These tend to be some of the stiffest requirements for determining "pass" or "fail" flammability status for a material.

10.2.2. AMINCO NBS Smoke Determination

This smoke test gives results in units of specific optical density ($D_s$) (ie. relating optical density to size of chamber, and surface area of sample exposed) and in theory directly comparable with other methods producing specific optical density values.

In comparing half inch thicknesses of fillers, latex under flaming conditions produced by far the worst level of smoke, (under flaming conditions all fillers lost at least 65% of their original weight), and failed to meet the requirements of the British Aircraft Corporation. In comparison to the other polyurethanes, fire retarded foam produced the highest rate of smoke increase. However, final levels were all equal (ie. at $D_{max} = 75 \pm 4$). Only rubberised hair produced more smoke under radiant than flaming conditions.
As expected PVC fabric produced the highest $D_{\text{max}}$ (ie. 215 after 1.8 minutes) and did not meet British Aircraft Corporation standards, being at least twice the level of any other fabric. Wool produced the next highest, and cotton-acrylic the lowest. Cotton-acrylic, wool-rayon and polyurethane fabrics all produced more smoke under radiant than under flaming conditions.

10.2.3 Vertical Flammability Tests

None of the materials met the British Aircraft Corporation standards, all burning for a considerable time after ignition with large weight loss. Only with wool and PVC fabrics was no afterglow observed and no burning droplets were observed with any of the fabrics.

There was no observable difference between warp and weft directions of weave in the cotton-acrylic and wool-rayon fabrics.

10.2.4 Horizontal Flammability Tests

All the fabrics passed under the Grade 3 requirements, except polyurethane fabric which passed under the Grade 4 requirements. Little significant difference was observed in tests in the warp and weft directions of weave for cotton-acrylic and wool-rayon or between two colours of cotton-acrylic fabric.

This test tended to bear out the case of fire spread being more difficult in a horizontal direction, than in a vertical direction.

10.2.5 Alcohol Cup Flammability Tests

None of the fabrics met the British Aircraft Corporation requirements, and cotton-acrylic, polyurethane and PVC fabrics were nearly burnt completely. Wool and wool-rayon only just failed by not meeting the
char width (ie. >2 inches). Wool proved most resistant to the alcohol flame, and was the only fabric not to burn through during test. No difference was observed between warp and weft directions in wool-rayon or cotton-acrylic fabrics or between different colours of the cotton-acrylic fabrics.

10.2.6 Critical Oxygen Index Test

All foams had low values of critical oxygen index and indicated self-supporting fire properties. The high resilience and non fire retarded foams both needed a reduction of oxygen concentration for them to be extinguished and meet the requirements of the test method. This indicates that both polyurethanes must be acting as their own fuel sources (eg. air from foam) once a flame is supported.

Wool, PVC and wool-rayon fabrics have higher than a critical oxygen index of 21% and suggests self-extinguishment.

10.2.7 Concluding General Comments

If these ten materials had been subjected to the above typical fire tests (with their stiff arbitrary pass conditions), none would have been accepted for manufacture into domestic furniture. (Wool might have proved a doubtful pass). It is unfortunate that no screening tests form part of the overall assessment materials undergo before being allowed to be used in furnishings. Ideally, materials should first be rated by small-scale tests, and those that pass should undergo a full scale test. Some criticism was made of small scale tests earlier, but if they are tied in with the findings of the full scale and to some extent those of mid scale tests, relevant standards may be assigned to them to produce significant values from the tests as they now stand.

A summary of results is shown in Appendix 1.4.
10.3 Thermal Analysis

As expected with these materials, (each of complex chemistry and compounding), information gleaned from differential thermal and thermogravimetric analyses was particularly sparse.

10.3.1. Differential Thermal Analysis

As already stated in Chapter 9.5 differential thermal analysis of the materials produced very limited data. The major transitions measured appeared to be related to the structural or chemical breakdown of the materials, when an exotherm indicated either pyrolysis or heat of depolymerisation.

No real difference was produced by varying heat rate, due to the low response of the apparatus under such conditions.

10.3.2. Thermogravimetric Analysis

In comparison with the differential thermal analysis, a greater mass of sample could be used and transitions were slightly easier to observe. The polyurethanes shows two major weight losses at 260 to 320°C and at 335 to 420°C. The former was probably due to depolymerisation and the formation of volatiles derived from isocyanate, and the latter due to the volatilisation of the polyol and the "yellow smoke". This smoke condensed on to the cooler surfaces of the apparatus.

The temperature of the first major transition for the polyurethanes was (in decreasing order): NFR HR FR which reflects the findings of the cigarette smoldering tests. The latex also goes through two transitions (ie. 285 to 295°C and 380 to 475°C). With rubberised hair there was a single major transition at 245 to 270°C.
Changing from an atmosphere of nitrogen (ie. inert) to that of air (ie. oxidative), caused the transitions of the polyurethanes and latex foam to drop in temperature, and weight loss to occur sooner, though the opposite occurred with rubberised hair. A minor transition was observed both wool and rubberised hair at around 100°C, which may have been due to water release from the the protein in the fibres.

The first major transition observed for all the fabrics was just over 300°C except for wool which had one at 250 to 305°C, the presence of wool in the wool-rayon fabric mix probably caused its reduction in major transition temperature.

Apart from the polyurethane foams, all materials heated remained at 20% of their original weight after test, in nitrogen or air, showing there may be a tendency for these materials to char. Since the exact elemental composition of the foams was unknown the 20% of the mass remaining can only be tentatively attributed to the carbon in the structure of the polymer. In comparing the materials with the high temperature resistant polymer, 'Nomex' very gradually lost weight on heating (at 550°C, 85% of the original weight remained and the sample showed little sign of char). Major transitions were observed at 450°C in nitrogen and above 625°C in air for the 'Nomex'. In comparison all the standard furnishing materials tested appeared to undergo breakdowns to volatiles at or before 300°C. As flaming ignition sources are well over 300°C, there is some indication that these materials (in whole or part) will undergo thermal breakdown in real-fires, however a polymer like 'Nomex' requires a far higher input of thermal energy to produce structural breakdown. It is therefore probable that thermogravimetric analysis shows this type of polymer to be far more resistant to minor fires.
10.3.3. Isothermal-gravimetric Analysis

None of the materials tested lost significant weight at 200°C, but at 300°C the following decrease of order in weight loss (after 20 minutes) was shown:

NFR ≡ HR PVC C/A FR W/R W RII PU L Nomex.

This may be relevant to fire testing if flammable gases are produced as part of the weight loss, but anomalies are indicated (e.g., PVC probably releases hydrogen chloride).

On the whole semi-micro thermal analysis gives a limited insight as to the possible reaction of material to fire, and due to the complexity of the polymeric forms used, data can only be used in a limited sense.
CHAPTER 11: CONCLUSIONS AND RECOMMENDATIONS
11.1 Preliminary Mid-Scale Fire Tests

The preliminary work showed that a mid-scale test facility had a potential use in the assessment of fire properties of domestic furnishing composites. However, problems arose in attempting to reproduce exact fire parameters, (as shown up in the Inter-Company Urethane Panel tests). It was found that the rig produced 'qualitative' rather than 'quantitative' values of temperature, smoke, toxic gas and weight loss. This was attributed to either properties purely related to scaling down, or more probably due to the positioning of the test samples (within the limitations of the apparatus). In addition dissatisfaction with the monitoring equipment indicated redesign or modification of the apparatus was required. The recent work was carried out to overcome these problems.

11.2 Recent Mid-scale Fire Tests

11.2.1. The chamber was reconstructed as a permanent metre cube in which any type to mid or small-scale fire test could be conducted, and be continuously monitored for atmospheric temperature rise, smoke production and carbon monoxide release.

11.2.2. Setting-up tests, based on the findings of the preliminary work, showed that a single piece foam sample (7.5 x 20 2cm³) ignited by a single or multi-point gas burner, did not completely burn (as might be expected from the Inter-Company Urethane Panel tests). It was felt that to achieve complete combustion, the burner would have to be extremely complex, and would produce a test method unrelated to the full scale tests.

11.2.3. Using multi-piece geometries of sample increased the complexities of overall burn. However, those geometries were perhaps closer to the
"chair-like" shapes of the full-scale test, and required alternative ignition sources than a gas flame. Burning newspaper was finally selected, performing in test with remarkable repeatability. Fire spread was rapid in these open geometries of sample, but the burn was still incomplete. This was shown to be partly due to the rapid heat loss from the fire centre to the atmosphere (resulting from the open structure and the particular dimensions of the sample which did not retain the generated heat), and possibly due to 'flame' effects (ie the holder masking the sample from the fire). However, it was established that sufficient air was present in the chamber to support full combustion.

It is recommended that any future scaled down rig should include a fire chamber which conforms to the geometry of the original full scale rig (eg. in this case living room shape).

Results paralleled the Inter-Company Urethane Panel findings, as in the preliminary tests, without producing exact values. Peak temperatures are of the same order. (note: temperature is related to material burnt and to sample and thermocouple positions), but toxic gas levels were lower (even after making allowances for incomplete combustion) It may be suggested that under combustion conditions, temperature (or heat release) maximums are less sensitive to minor test set ups, than resultant gas levels. Smoke build up was rapid as in the Inter-Company Urethane Panel tests, but unfortunately no full comparison can be made as there is still no way of fully correlating smoke data.

Fabric covering the foam had overriding effects. The surface area of sample exposed initially was far greater than the fabric coverage, so
the test took on an artificial status by the inclusion of an excessive area of glasscloth (i.e., an inert fabric covering). The significance of a fabric covered multi-piece sample in this test was probably limited to the ignition and early propagation stages of fire, since the glasscloth will make its own contribution to fire spread in the later stages. Nevertheless, the test data produced showed the fabrics led to fires of measurable differences. Wool slowed fire into non-fire retarded foam better than any other fabric, and polyurethane fabric produced the worst pyrolytic conditions. All combinations reached a maximum temperature of 450°C.

11.2.4 Using a paper ignition source, fire tests on the more confined geometry of the 7.5 x 20² cm³ sample were continued. The greater extent of burn in the uncovered fillers showed that an ignition source which was in contact with the sample longer (even if at a cooler flame temperature) was more effective than a gas flame. This possibly gives rise to a more oxidative combustion and lower levels of toxic gases than found either by the Inter-Company Urethane Panel or in the preliminary tests. In terms of overall fire resistance to flaming ignition, the uncovered fillers in vertical mode had the following decreasing order of resistance: FR HR NFR ≡ L ≡ HH

It was shown that the fabrics, covering non-fire retarded foam, have significant influence in the resulting flammability of the composite. This was particularly shown in the horizontal modes of test. The ignition source on top of wool or wool-rayon covered non-fire retarded foam did not burn, while the others slowed the fire depending on their flammability characteristics. (These tests showed that a proper form of small-scale fire test could have some relevance in assessing the fire properties of fabrics). The vertical modes readily burned, the fabrics producing
greater pyrolysis. It is thought these types of test are relevant to full scale fires, showing the manner in which part of a chair (eg. arm rest) might react to fire.

11.2.5 Cigarette smoldering tests showed that the resistance of the filler to the low temperature smolder, may be scaled primarily in relationship to their heat resistance (cf. thermogravimetric analysis data), although the structure of filler must be also taken into account ie. in decreasing order: FR L HR NFR RH.

Fabric covering had a significant effect on the smoldering properties, dependent on the burn through resistance, heat transfer and the type of char formed by the fabrics. From this work, the fabrics were scaled to cigarette resistance in decreasing order: W W/R PU C/A, with the former two materials very resistant. However, there appears to be certain fillers (eg. high resilience foam) which overrode the shielding effect of the fabrics (except wool), and readily pyrolised.

Most of the mid-scale tests showed they made definite contributions to the understanding of fires in domestic furnishing composites, indicating what combinations produced the best fire resistance, (if any). However, in terms of parallelling full-scale tests, there are severe problems, related to reproducing the exact conditions that exist in real fires (eg. it is impossible to cover samples completely) and the effects on the overall fire. Many of the tests employed were relevant in establishing the manner in which a fire proceeds in its early stages (ie. ignition and first stages of propagation), but were limited in the determination of relevant data from the latter stages of propagation and termination of the fire. The medium scale test has a place in a full programme of fire tests for materials, with its ability to look
at particular geometries of composites and assessing which way they will act in a fire. A basic test method has been designed, but exact usage will stem from the mode of burn required.

It is worth suggesting that some form of legislation be constructed which will demand that the filler and fabric, or the furniture manufacturers conduct some forms of small scale fire testing to evaluate materials prior to their use in furnishings, with a "pass" or "fail" standard determined from either a medium or full scale fire test.

The original design of rig, allowed for the testing of a wide range and type of composite, and therefore a one metre cube was selected as a convenient size. However to draw true parallels with living room or even warehouse fires, demands a range of chamber geometries available for particular tests, along with semi-permanence of monitoring equipment that may be quickly interchanged among the rigs.

11.3 Small Scale Fire Tests

The critical oxygen index tests showed the fillers to have little or no fire-resistance, but some of the fabrics had limited resistance.

All flammability tests showed the poor fire resistance of the fabrics. As previously commented, if due regard had been made to these sorts of test, alternative material might have been used in the mid and full scale tests. The smoke test showed that PVC and latex foam were by far the worst smoke producers.

11.4 Semi-micro Thermal Analysis

The complex nature of the materials prevented much information to be gained from differential thermal analysis. Thermogravimetric analysis showed all these materials to degrade and lose considerable weight by 300°C (ie.
well below the average flaming ignition source temperature), and out of the two semi-micro techniques thermogravimetric analysis perhaps has some application in establishing the relative heat resistance of materials, (but probably only in terms of low temperature smoldering).
APPENDIX 1 : TEST RESULTS
### A.1.1. Preliminary Test Results: Temperature and Weight Loss.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Max. Temp Recorded at 15 (°C)</th>
<th>Time to Maximum at 15 (sec)</th>
<th>Maximum Temp Recorded at 13 (°C)</th>
<th>Maximum Temp Recorded at 11 (°C)</th>
<th>Maximum Temp Recorded at 3 (°C)</th>
<th>Maximum Temp Recorded at 5 (°C)</th>
<th>Time Above 200°C (sec)</th>
<th>Total Burn Time (sec)</th>
<th>Weight Loss (%)</th>
<th>No. of Samples</th>
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Positioning of Thermocouples: 15 Flexi probe at centre of sample
13 MM
11 MT
1 RB
3 BM
5 WR
### A.1.1. Preliminary Test Results: Smoke and Toxic Gases

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*All Toxic Gas measured by Drägers except ☞, carried out by wet analysis (large quantities of CO₂, indicated by IR from wet analysis samples).

* Dip in smoke trace due to illumination of fire being greater than optic's output.
### A.1.2. Results of Medium Scale Tests: Temperature/Wt. Loss

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<th>Max. at 3 °C</th>
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## A.1.2. Results of Medium Scale Tests: Temperature/Wt. Loss (Contd.)

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+ Did Not Burn With Flame but Had Afterglow
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NR: Not Recorded

\(\odot\): Fluctuation Did Not Allow Precise Measurement To Be Made

\(\odot\): Did Occur In The Trace Due to Illumination By The Fire.
### A.1.3. Cigarette Smoldering Results

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<th>Max. CO (ppm)</th>
<th>HCN (ppm)</th>
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<th>Char Height (cm)</th>
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* Full Burn Time = Time for cigarette tobacco to be completely burnt (indicated by mark)

** Full Burn Time = Time for tobacco to be half burnt (indicated by mark)

NR = Not Recorded

Smoldering of Cigarette Alone:

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Max. Temp (°C)</th>
<th>Time to Max. Temp (min)</th>
<th>Rate of Temp. Increase (°C/m)</th>
<th>Time to Max. Rate (min)</th>
<th>Time Above 200°C (min)</th>
<th>Wt. Loss (%)</th>
<th>Max. CO (ppm)</th>
<th>HCN (ppm)</th>
<th>** Full Burn Time: (min)</th>
<th>** Half Burn Time: (min)</th>
<th>Char Height (cm)</th>
<th>Char Length (cm)</th>
<th>Char Width (cm)</th>
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### A.1.4 Small Scale Tests: AMINCO-NBS Smoke Determination

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<th>Material</th>
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<th>Condition</th>
<th>Dm corrected</th>
<th>Time to Dm (min)</th>
<th>Time to 90% Dm (min)</th>
<th>Dm -1</th>
<th>Dm-2 -1</th>
<th>Dm-3 -1</th>
<th>Dm-4 -1</th>
<th>Dm-5 -1</th>
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<th>No. of Samples</th>
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<td>59</td>
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B.A.C. Standards: To Pass Dm < 100 at 1 minute, and < 200 at 2 minutes.

All Samples Preconditioned at 23°C and 50% RH.

+ Smoldering Burnt with Flame
### A.1.4. Small Scale Tests: Vertical Flammability Test

<table>
<thead>
<tr>
<th>Material</th>
<th>Test Direction</th>
<th>Thickness (inch)</th>
<th>Bunsen Burn Time</th>
<th>Char Height (inch)</th>
<th>Char + Width (inch)</th>
<th>Afterburn Time (sec)</th>
<th>Afterglow Time (sec)</th>
<th>Drip Time (sec)</th>
<th>Wt. Loss (%)</th>
<th>No. of Samples</th>
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<td>&gt;1.8</td>
<td>70</td>
<td>0</td>
<td>0</td>
<td>37</td>
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<td>&gt;120</td>
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<td>105</td>
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*Grade + .... 1.8" = Frame Width.*
### A.1.4 Small Scale Tests: Horizontal Flammability Test

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<th>Test Direction</th>
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<th>Bunsen Burn Time (sec)</th>
<th>Time Alight after pass 1st line (sec)</th>
<th>Time Between 10 inch Span (sec)</th>
<th>Rate (inch/min)</th>
<th>Dist Burn Beyond 1st mark (inch)</th>
<th>Weight loss (%)</th>
<th>No. of Samples</th>
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<td>3</td>
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NR = Not Reached
### A.1.4. Small Scale Tests: 45° Alcohol Cup Test (0.7cc 80° Industrial Alcohol)

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<th>Test Direction</th>
<th>Thickness (inch)</th>
<th>Char Height (inch)</th>
<th>Char Width (Inch)</th>
<th>Burn *</th>
<th>Burn Through Time (sec)</th>
<th>Weight Loss (%)</th>
<th>No. of Samples</th>
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<td>&gt;7</td>
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<td>&gt;7</td>
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* Included Afterglow time N.R. - Not Reached

### A.1.4. Small Scale Tests: Critical Oxygen Index Test (to ASTM D 2863)

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* The oxygen requirement for ignition was first figure indicated but material would not extinguish with the required time of 3 minutes until oxygen concentration reduced to second figure.

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<th>AMINCO-NBC CHAMBER:</th>
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<th>Horizontal Fire Test</th>
<th>45° Alcohol Cup Test</th>
<th>Critical Oxygen Test</th>
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<td>Grade 2 Burn Length = 8&quot; max</td>
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<td>Afterflame = 15 sec max.</td>
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<td>Ds &lt;200 at 2 min</td>
<td>After Flame = 15 sec</td>
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<td>FAIL Char Width &gt;2&quot;</td>
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### A.1.4. Small-Scale Test: Synopsis of Small-Scale Test (Contd.)

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<td>Ds &lt; 100 at 1 min&lt;br&gt;Ds &lt; 200 at 2 min</td>
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<td>Grade 3&lt;br&gt;Burn Rate = 2.5&quot;/min</td>
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<td>Cotton/Acrylic</td>
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<td>FAIL&lt;br&gt;Total Incineration</td>
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A.1.5 Semi-micro Thermal Analysis Results: Thermogravimetric Analysis (Flow rate = 40cc/min).

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A.1.5 Semimicro Thermal Analysis Results: Thermogravimetric Analysis (Flow rate = 40cc/min). (Contd.)

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* Nomex used as a comparator - as a high-temperature resistant polymer
### A.1.5. Semi-micro Thermal Analysis Results: Isothermogravimetric Analysis (Flow rate = 40 cc/min)

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APPENDIX 2 : GRAPHS

Contents:
A.2.1. Some Preliminary Test Graphs
A.2.2. Mid Scale Test Graphs
A.2.3. Some Smoldering Test Graphs
A.2.4. Typical Thermogravitmetric Thermograms
Temperature (at TCs 1, 2, 3, 4)

- TC 15
- TC 13
- TC 11

Temperature (at TCs 5, 6, 7)

- TC 2
- TC 3
- TC 1

Smoke levels

- Time (min): 0, 1, 2, 3, 4, 5, 6

CO levels

- Time (min): 0, 1, 2, 3, 4, 5, 6

Soot corr. 

- Time (min): 0, 1, 2, 3, 4, 5, 6

Other Observations:

- Burn pattern
- Dräger analysis:
  - NOx: 250 ppm
  - HCN: 7 ppm
  - HCl: / ppm
- Weight loss: / %
- CO: 450 ppm

X represents ignition point.

Sample Reference: 14 [NFR]
Temperature (at TCS 5, 13, 31):

key: TC 15
TC 18
TC 11

Smoke levels:

- Time (min)

- CO levels

Soot corr.: -20 O.D.

Other Observations:

Burn pattern:

- Burn time:
- Dräger analysis:
  - NOx < 100 ppm
  - HCN: 20 ppm
  - HCl: / ppm
  - Weight loss: 44%
  - CO: 350 ppm

X: represents ignition point.

Sample Reference: 17 (FR)
Temperature (at TCs 5, 6, 7, 8)
key: --- TC 5
----- TC 6
-------- TC 7
---------- TC 8

Temperature (at TCs 5, 6, 7, 8)
key: --- TC 5
----- TC 6
-------- TC 7
---------- TC 8

Smoke levels

CO levels

Smoke (m.t.D.)

Conc.\n
Soot corr = x: O.D.

Other Observations:

Burn pattern:

Burn time: seconds.

Dräger analysis:

NO\textsubscript{x}: 150 ppm

HCN: 12.5 ppm

HCl: / ppm

Weight loss: 79 %

CO: 850 ppm

X\ldots\ldots \text{represents ignition point.}

Sample Reference: 4.8 (HR)
Sample Reference: 4.9 (L)
Other Observations:

- Burn pattern:
- Burn time: [seconds]
- Dräger analysis:
  - NO\textsubscript{x}: 150 ppm
  - HCN: 120 ppm
  - HCl: / ppm
- Weight loss: 100 %
- CO: 6000 ppm

X represents the ignition point.

Sample Reference: A.10 (RH)
Sample Reference: 142 (NFR - W)
**Other Observations**

- Burn pattern: ... 
- Burn time: 1,440 seconds. 
- Dräger analysis:
  - NO\textsubscript{x}: 200 ppm. 
  - HCN: 38 ppm. 
  - HCl: ... ppm. 
- Weight loss: 4.9% 
- CO: >3000 ppm. 

X ... represents ignition point.

Sample Reference: 144. (NFR-WR)
Temperature (at TCs 15, 13, 11)

- TC 15
- TC 13
- TC 11

Temperature (at TCs 5, 3, 1)

- TC 5
- TC 3
- TC 1

Smoke levels

- 1
- 2
- 3
- 4
- 5

Time (min)

CO levels

- 0
- 500
- 1000
- 1500
- 2000
- 2500
- 3000
- 3500

CO conc. (ppm)

Soot corr. = 0.000 D.O.

Other Observations:

- Burn pattern
- Dräger analysis:
  - NOx: 2.00 ppm
  - HCN: 75 ppm
  - HCl: / ppm
- Weight loss: 74%
  - CO (3000 ppm)

X... represents ignition point.

Sample Reference: 115 [NFR-PU]
Temperature (at TCs 1, 2, 3)

Temperature (at TCs 4, 5, 6)

Smoke levels

CO levels

Soot corr. to O.D.

Burn pattern

Sample Reference: 2.4 (NFR in 1G Geometry with Mesh, 1/4 of Back Wall)
Temperature (at TCs 1, 2, 3)

key: TC 1
TC 2
TC 3

Temperature (at TCs 4, 5, 6)

key: TC 4
TC 5
TC 6

Smoke levels

Smoke (D.D.)

Conc.

0.0

1.0

1.5

2.0

3500 CO levels

CO (ppm)

0.0

50.0

100.0

150.0

200.0

250.0

300.0

350.0

400.0

450.0

500.0

600.0

700.0

800.0

900.0

1000.0

1100.0

1200.0

1300.0

1400.0

1500.0

1600.0

1700.0

1800.0

1900.0

2000.0

2100.0

2200.0

2300.0

2400.0

2500.0

2600.0

2700.0

2800.0

2900.0

3000.0

3100.0

3200.0

3300.0

3400.0

3500.0

3600.0

3700.0

3800.0

3900.0

4000.0

4100.0

4200.0

4300.0

4400.0

4500.0

4600.0

4700.0

4800.0

4900.0

5000.0

5100.0

5200.0

5300.0

5400.0

5500.0

5600.0

time (min)

0

1

2

3

4

5

6

7

time (min)

0

1

2

3

4

5

6

Other Observations:

Burn pattern:

Burn time: 210 seconds.

Dräger analysis:

NOx: 200 ppm.

HCN: 11 ppm.

HCl: 0 ppm.

Weight loss: 73 %.

Sample Reference: 2.2 (NFR 4c Geometry With Mesh)

As midpoint of testwall
Temperature (at TCs 1, 2, 3)

key: ——— TC 1
     ———— TC 2
     ———— TC 3

Temperature (at TCs 4, 5, 6)

key: ——— TC 4
     ——— TC 5
     ——— TC 6

Smoke levels

CO levels

Other Observations:

Burn pattern:

X represents ignition point.

Sample Reference: 2, 3

(NFR)
Temperature (at TCs 1, 2, 3)

key:
- TC 1
- TC 2
- TC 3

Temperature (at TCs 4, 5, 6)

key:
- TC 4
- TC 5
- TC 6

Smoke levels

0.0
0.5
1.0
1.5

Smoke (absorbance)

conc.

soot corr.: 0.3 OD.

CO levels

0
1000
2000
3000
4000
5000

ppm

time (min)

Other Observations:

Burn pattern:

- Burn time: 345 seconds.
- Dräger analysis:
  - NO_x: 160 ppm
  - HCN: 9 ppm
  - HCl: 1 ppm
- Weight loss: 66%

X... represents ignition point.

Sample Reference: 24 (NFR in 53 Commanding War Match)
Temperature (at TCs 1, 2, 3)

Temperature (at TCs 4, 5, 6)

Smoke levels

CO levels

Other Observations:

Burn pattern:

Burn time: 420 seconds

Dräger analysis:

\( \text{NO}_x \): 130 ppm

\( \text{HCN} \): 5 ppm

\( \text{HCl} \): 0 ppm

Weight loss: 77%

Sample Reference: 25 (NEF) in 31 Geometry with RE Paper at Base Of Beacham
Temperature (at TCs 1, 2, 3)
- \( T C_1 \)
- \( T C_2 \)
- \( T C_3 \)

Temperature (at TCs 4, 5, 6)
- \( T C_4 \)
- \( T C_5 \)
- \( T C_6 \)

Smoke levels
- Smoke conc.: 0.5 to 2.0
- Soot corr. = 0.4 O.D.

Other Observations:
- Burn pattern:
  - X represents ignition point.

- Burn time: 400 seconds.
- Dräger analysis:
  - \( NO_x \) < 100 ppm
  - HCN = 3 ppm
  - HCl = ppm
- Weight loss: 67%

Sample Reference: NFR In 2c Geometric Way, #4 Paper At Apex
Temperature (at TCs 1, 2, 3)

Temperature (at TCs 4, 5, 6)

Smoke levels

CO levels

Other Observations:

Burn pattern:

Dräger analysis:

- NOx: <100 ppm
- HCN: 4 ppm
- HCl: 0 ppm

Weight loss: 67%

Sample Reference: 2.7 (NFR in '10, Geometry: Wall 2, Airflow: 1/3 of Paper at Base of Sidewalls)
Temperature (at TCs 1, 2, 3)

Temperature (at TCs 4, 5, 6)

Smoke levels

CO levels

Soot corr. = 200 O.D.

Other Observations:

Burn pattern:

Burn time: 320 seconds.

Dräger analysis:

NOx: 200 ppm.
HCN: 5 ppm.
HCl: ppm.

Weight loss: 34%.

X ... represents ignition point.

Sample Reference: 23 (NFR)
**Temperature (at TCs 1, 2, 3)**

- **Key:**
  - TC 1: Solid line
  - TC 2: Dashed line
  - TC 3: Short dashed line

**Temperature (at TCs 4, 5, 6)**

- **Key:**
  - TC 4: Solid line
  - TC 5: Dashed line
  - TC 6: Short dashed line

**Smoke levels**

- **Time (min):** 0, 1, 2, 3, 4, 5, 6
- **Smoke (E.O.D.):** 0, 0.5, 1, 1.5, 2.0

**CO levels**

- **Time (min):** 0, 1, 2, 3, 4, 5, 6
- **CO (ppm):** 0, 500, 1000, 1500, 2000, 2500, 3000

**Other Observations:**

- **Burn pattern:**
- **Burn time:** 300 seconds
- **Dräger analysis:**
  - NOx: 110 ppm
  - HCN: 3 ppm
  - HCl: / ppm
- **Weight loss:** 46 %

- **Soot corr.:** 0.04 E.O.D.

- **X** represents ignition point.

Sample Reference: 2.9 (NFR) 10 min cube with As paper
Temperature (at TCs 1, 2, 3)

key: --- TC 1
     ..- TC 2
     ..-- TC 3

Temperature (at TCs 4, 5, 6)

key: --- TC 4
     ..- TC 5
     ..-- TC 6

Other Observations:

Burn pattern:

Dräger analysis:

NOx: 110 ppm
HCN: 3 ppm
HCl: / ppm

Weight loss: 45%

Sample Reference: 2.10 (NFR)

Paper On: Top Centre
Temperature (at TCs 1, 2, 3)

\[ \text{Temperature (at } \text{TCs 4, 5, 6)} \]

Smoke levels

\[
\begin{array}{c}
\text{time (min)}
\end{array}
\]

\[
\begin{array}{c}
\text{time (min)}
\end{array}
\]

\[
\begin{array}{c}
\text{time (min)}
\end{array}
\]

Other Observations:

- Burn pattern:
- Dräger analysis:
  - NO\(_x\): <100 ppm
  - HCN: 2 ppm
  - HCl:  ppm
- Weight loss: 64%

Sample Reference: 2.15  (NFR - 1/2 Geometry with 2.4m Paper At Base 0.5m Sides, 50m 400m High Ceiling)
Temperature (at TCs 1, 2, 3)

key: 
- TC 1
- TC 2
- TC 3

Smoke levels

temp. (°C)

3500 CO levels
time (min)

0 1 2 3 4 5 6

0 1 2 3 4 5 6

time (min)

Burn pattern:

X represents ignition point.

Other Observations:

Burn time: 480 seconds.

Dräger analysis:

NO\textsubscript{x}: 100 ppm
HCN: 3 ppm
HCl: / ppm

Weight loss: 32 %

Sample Reference: 2.16 (NFR 75 x 300°C Horizontal Burn: As Phosphor)
Centre, with 30 cm Hg Cooling)
Other Observations:

Burn pattern:

Burn time: 215 seconds.

Dräger analysis:
- NO<sub>x</sub>: ≤100 ppm.
- HCN: 12 ppm.
- HCl: ppm.

Weight loss: 74%.

X... represents ignition point.

Sample Reference: 2.17 (NFR: 12 Geometry, NM 2, Air Paper Per Side; Notes: with 30mm High Aluminium Covered Ceiling.)
Other Observations:

- Burn pattern:

<table>
<thead>
<tr>
<th>Sample Reference</th>
<th>2.18 (NFR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry:</td>
<td>With 2x44 Paper At Side</td>
</tr>
<tr>
<td>Weight loss:</td>
<td>89%</td>
</tr>
</tbody>
</table>

X ... represents ignition point.

Burn time: 250 seconds.

Dräger analysis:

- NOx: <100 ppm
- HCN: 0.2 ppm
- HCI: / ppm
Temperature (at TCs 1, 2, 3)

Temperature (at TCs 4, 5, 6)

Other Observations:

Burn pattern:

X represents ignition point.

Sample Reference: 2.19 (NFR-W)

10' Geometry With 2' Air Flow At 5' Side Wall With A Wooden Sample Holder
Temperature (at TCs 1, 2, 3)

- TC 1
- TC 2
- TC 3

Temperature (at TCs 4, 5, 6)

- TC 4
- TC 5
- TC 6

Smoke levels

- 1.0
- 1.5
- 2.0

Smoke concn. (A.D.)

- 0.5
- 1.0
- 1.5

CO levels

- 1500
- 2000
- 2500

CO concn.

- 1000
- 1500
- 2000

Soot corr.: 500 A.D.

Other Observations:

- Burn pattern
- Dräger analysis:
  - NOx: <100 ppm
  - HCN: 5 ppm
  - HCl: 1 ppm
- Weight loss: 38%

X represents ignition point.

Sample Reference: 220 (NFR-CA 14: Geometry Wire 2,44 Paper: Al S1, K1, T1, T2, T3, Glasscloth)
Sample Reference: 2.21. (NFR-W)
Sample Reference: 2.22. (NFR-CA L 4 Geometry 2m 2 A4)

Paper at side walls
Other Observations:

Burn pattern:

Burn time: 630 seconds.

Dräger analysis:

\[ \text{NO}_x: 200 \text{ ppm} \]
\[ \text{HCN}: 60 \text{ ppm} \]
\[ \text{HCl}: / \text{ ppm} \]

Weight loss: 60%

X ... represents ignition point.

Sample Reference: 2.23 (NFRW 1c Geometry with 2-A4, Fayer At Side Walls)
Temperature (at Tc 1, 2, 3):

- Tc 1
- Tc 2
- Tc 3

Temperature (at Tc 4, 5, 6):

- Tc 4
- Tc 5
- Tc 6

Smoke levels

- Smoke (0-2)

CO levels

- CO (0-3500 ppm)

Soot concentration

Other Observations:

- Burn pattern
- Dräger analysis:
  - NO:< 200 ppm
  - HCN: < 50 ppm
  - HCl: < ppm
- Weight loss: 56%

X represents ignition point.

Sample Reference: 2.24 (NFRWR)

Paper: At 5th Wall
Temperature at TCS 1, 2, 3

Temperature at TCS 4, 5, 6

Other Observations:
- Burn pattern
- Burn time: 180 seconds
- Dräger analysis:
  - NO<sub>x</sub>: 150 ppm
  - HCN: 75 ppm
  - HCl: ppm
- Weight loss: 72%

X represents ignition point.

Sample Reference: 2.25 (NFR-PU 1c Geometry Unit 2-4k Paper At Side Walls)
Temperature at TCs 1, 2, 3
key: --- TC 1
- - - TC 2
..... TC 3

Temperature at TCs 4, 5, 6
key --- TC 4
- - - TC 5
..... TC 6

Smoke levels 0 1 2 3 4 5
Time(min) 0 1 2 3 4 5

Smoke concn 0.5 1.0 1.5 2.0

Soot corr : O.D.

Other Observations:
Burn pattern:
Drager analysis:
NOx: 260 ppm
HCN: 35 ppm
HCl: ppm
Weight loss: 35 %

X represents ignition point.

Sample Reference: 2.26 (NFR 73 x 20° Sc Vertical with A+ Paper Centrally Under Base)

312
Temperature (at TCs 1, 2, 3)

Key:
- TC 1
- TC 2
- TC 3

Temperature (at TCs 4, 5, 6)

Key:
- TC 4
- TC 5
- TC 6

Smoke levels

CO levels

Burn time: 120 seconds.

Dräger analysis:
- NO₂ ≤ 100 ppm
- HCN ≤ 50 ppm
- HCl ≤ ppm

Weight loss: 22%

Other Observations:
- Burn pattern
- X represents ignition point

Sample Reference: 2.27 (FR 7.5×20°ed Vertical, With A4 Paper Centrally Under Base)
Temperature (at Tcs 1, 2, 3)
key: — TC 1
—- TC 2
—-.. TC 3

Temperature (at Tcs 4, 5, 6)
key: — TC 4
—- TC 5
—-.. TC 6

Smoke levels

CO levels

Soot concn. x 100 ppm

Other Observations:

Burn pattern:

Burn time: 155 seconds.

Dräger analysis:

NO₂: <100 ppm.

HCN: 21 ppm.

HCl: / ppm.

Weight loss: 76%.

X ... represents ignition point.

Sample Reference: 2.28 (HR 7.9 x 90°, Vertical with A4 Page Centre, Under Base)
Other Observations:

Burn pattern:
- Foam shrunk up from original shape
- (loosening cellular structure)

Burn time: 30 seconds

Dräger analysis:
- NO\(_x\): / ppm
- HCN: 3 ppm
- HCl: / ppm

Weight loss: 24 %

X... represents ignition point.

Sample Reference: 2, 29 (L 7.9 x 500 cc Vertical With Air: Paper Centrally Under Base)
Temperature (at TCs 1, 2, 3):
- Key: ______ TC 1
- ______ TC 2
- ______ TC 3

Temperature (at TCs 4, 5, 6):
- Key: ______ TC 4
- ______ TC 5
- ______ TC 6

Other Observations:
- Burn pattern: Only Ash Remained
- Dräger analysis:
  - NOx: 220 ppm
  - HCN: 75 ppm
  - HCl: / ppm
  - Weight loss: 100 %

X ... represents ignition point.

Sample Reference: 2.30 (RH 75% x 20°C) Vertical, with NH4 Paper (Centrally under Fixture)
Temperature (at TCS 1, 2, 3)

key:
--- TC 1
--- TC 2
--- TC 3

Temperature (at TCS 4, 5, 6)

key:
--- TC 4
--- TC 5
--- TC 6

Smoke levels

--- smoke correction: 0 O.D.

CO levels

0 1 2 3 4 5 6 time (min)
0 1 2 3 4 5 6 time (min)

Other Observations:

Burn pattern:

Dräger analysis:

NOx: 280 ppm
HCN: >150 ppm
HCl: / ppm
Weight loss: 7.2%.

X... represents ignition point.

Sample Reference: 2.31 (NFR W7.5 x 20°C Vertical, 0.5 mm Al)
Paper: Centrally Under, Base
Temperature (at Tcs 1, 2, 3)

Key:
- TC 1
- TC 2
- TC 3

Temperature (at Tcs 4, 5, 6)

Key:
- TC 4
- TC 5
- TC 6

Smoke Levels

Time (6 min)

3500 CO Levels

Time (min)

Soot corr: 30% O.D.

Other Observations:

Burn pattern

Dräger analysis:
- NO₂: 130 ppm
- HCN: 120 ppm
- HCl: ppm

Weight loss: 63 %

X ... represents ignition point.

Sample Reference: 2.3.2 (NFR-CA 7.8 20°C Vertical with Air)
Other Observations:

- Burn pattern:
- Dräger analysis:
  - NO: 150 ppm
  - HCN: 65 ppm
  - HCl: ppm
- Weight loss: 69%

Sample Reference: 2.33 (NFR-WR)
Sample Reference: 2.34. (NFR - PU 75 x 25°c Vertical, with A.G.)
Other Observations:

Burn pattern:

Burn time: 22.5 seconds.

Dräger analysis:

- NO\textsubscript{x}: 100 ppm.
- HCN: >75 ppm.
- HCl: 1 ppm.
- Weight loss: 72%.

X... represents ignition point.

Sample Reference: 2.35 (NFR-PVC, 7x50cm Vertical, with A4 Paper; Centrally Under Base)
Temperature (at TCs 1, 2, 3)

- Temperature (at TCs 4, 5, 6)

Smoke levels

CO levels

Smoke concentration

Other Observations:

Burn pattern:
- Only fragments of rubberized hair and cotton-acrylic remaining

Burn time: 180 seconds.

Dräger analysis:
- NOx: 130 ppm
- HCN: 65 ppm
- HCl: 7 ppm
- Weight loss: 86%

X: represents ignition point.

Sample Reference: 2.37 (RH-CA 7.8 x 20°C Vertical, 5 min, A4) (Pb/Centrally Under Brahm)
Temperature (at TCS 1, 2, 3)

Key: ——— TC 1
      ——— TC 2
      ——— TC 3

Temperature (at TCS 4, 5, 6)

Key: ——— TC 4
      ——— TC 5
      ——— TC 6

Smoke levels

Other Observations:

Burn pattern:

Dräger analysis:

- NO₂: 14 ppm
- HCN: 60 ppm
- HCl: / ppm

Weight loss: 95 %

X: ... represents ignition point.

Sample Reference: 2.32 (NFR-CA 75 x 200cc Horizontal with AA paper, Centrally on Top)

324
Temperature (at TCs 1, 2, 3)

Key:
- TC 1
- TC 2
- TC 3

Temperature (at TCs 4, 5, 6)

Key:
- TC 4
- TC 5
- TC 6

Smoke levels

3600 CO levels

Other Observations:

Burn pattern:
- Only Smoke Oozing
- Occluded

Burn time: <150 seconds (did not burn)

Dräger analysis:
- NOx: 0 ppm
- HCN: 0 ppm
- HCl: 0 ppm

Weight loss: 0 %

X represents ignition point.

Sample Reference: 2239 (NFR-W: 75 x 30sec horizontal, with A+ Paper Centrally On, Tip)
Other Observations:

Burn pattern:
- Only slight charring occurred.

Burn time: <180 seconds.

Dräger analysis:
- NOx: 0 ppm
- HCN: 0 ppm
- HCl: 0 ppm
- Weight loss: 0%

X... represents ignition point.

Sample Reference: 2.40 (NFR-1/W2) 75x25cc, Horizontal, with
A+ Paper Centrally on Top
Burn pattern: 4-500 seconds

Dräger analysis:
- NO₂: <100 ppm
- HCN: 20 ppm
- HCI: <1 ppm

Weight loss: 84 %

Sample Reference: 2.4.1 (NFR-PU 7.5 x 2.50 Horizontal, 60mm. A 4 Tube Ombing On Top)
Temperature (at TCs 1, 2, 3)
Key: -- TC1
- - - - - - TC2
- - - - - - TC3

Temperature (at TCs 4, 5, 6)
Key: -- TC4
- - - - - - TC5
- - - - - - TC6

Other Observations:
- Burn pattern:

Burn time: 4.80 seconds.
- Dräger analysis:
  - NO$_2$: ≤400 ppm.
  - HCN: 10 ppm.
  - HCl: / ppm.
  - Weight loss: 4.6%.

X:... represents ignition point.

Sample Reference: 2.4-2 [NFR-PVC 7.5 x 30° CE, Mitred, Joint, A Paper/Central on Tip]
Temperature (at TCs 1, 2, 3)

key: TC1  TC2  TC3

Temperature (at TCs 4, 5, 6)

key: TC4  TC5  TC6

Smoke levels

3000 CO levels

Smokecontent

sootcorr = 50 x O.D.

Other Observations:

- Burn pattern:
- Dräger analysis:
  - NOx: 440 ppm
  - HCN: 35 ppm
  - HCl: 7 ppm
- Weight loss: 48%

X... represents ignition point.

Sample Reference: 2.4.3 (NFR)
Other Observations:

- Burn pattern:

- Dräger analysis:
  - NOx: <100 ppm
  - HCN: 40 ppm
  - HCl: / ppm

- Weight loss: 81%

X ... represents ignition point.

Sample Reference: 2.4.4: (NFR - W)
Sample Reference: 2.45 (NFR-WR)

Other Observations:

Burn pattern:

- Burn time: 210 seconds.
- Dräger analysis:
  - NO₂: <100 ppm.
  - HCN: 30 ppm.
  - HCl: 0 ppm.
- Weight loss: 13%.

X ... represents ignition point.
**Other Observations:**

- **Burn pattern:**
- **Burn time:** 190 seconds.
- **Dräger analysis:**
  - NO$_x$: 30 ppm.
  - HCN: 25 ppm.
  - HCl: / ppm.
- **Weight loss:** 48 %.

- X represents ignition point.

**Sample Reference:** 2.4-6 (NFR)
Temperature (at Tcs 1, 2, 3)

Key:
- TC 1
- TC 2
- TC 3

Temperature (at Tcs 4, 5, 6)

Key:
- TC 4
- TC 5
- TC 6

Other Observations:

Burn pattern: Only Fragments Remaining

Burn time: 195 seconds.

Dräger analysis:
- NO₂: 1200 ppm
- HCN: 125 ppm
- HCl: / ppm

Weight loss: 93%

X... represents ignition point.

Sample Reference: 2.47: (NFR - W) 78% x 56% Horizontal, with Air
Paper Centrally Under Base
**Other Observations:**

- **Burn pattern:** Sample completely destroyed.
- **Burn time:** 330 seconds.
- **Dräger analysis:**
  - NO<sub>x</sub>: 150 ppm.
  - HCN: 75 ppm.
  - HCl: / ppm.
- **Weight loss:** 100 %.

X... represents ignition point.

**Sample Reference:** 2.48 (NFR - CA)
The diagram shows the temperature over time for two sets of thermocouples (TCs 1, 2, 3 and TCs 4, 5, 6) along with smoke and CO levels. The data includes:

- **Temperature (at TCs 1, 2, 3)**
  - Key:
    - TC 1
    - TC 2
    - TC 3

- **Temperature (at TCs 4, 5, 6)**
  - Key:
    - TC 4
    - TC 5
    - TC 6

**Other Observations**

- **Burn pattern**
- **Burn time**: 195 seconds.
- **Dräger analysis**:
  - NOx: 1.20 ppm
  - HCN: 80 ppm
  - HCl: / ppm
- **Weight loss**: 70%

X... represents ignition point.

Sample Reference: 2.4-9 (NFR-WR 7.8 x 30° on Horizontal, warm, A4)

Paper Centrally Under Base
Temperature (at TCS 1, 2, 3)

Key:
- TC1
- TC2
- TC3

Temperature (at TCS 4, 5, 6)

Key:
- TC4
- TC5
- TC6

Temperature (°C)

Smoke levels

CO levels

Smoke concentration

Soot corr n = 0.3 D.O.

Other Observations:

Burn pattern:
Very Little Remaining

Burn time: 420 seconds.

Dräger analysis:
- NOx: 100 ppm
- HCN: 50 ppm
- HCl: ppm

Weight loss: ~100%

X... represents ignition point.

Sample Reference: 250 (NFR-PU)
Temperature (at TCs 1, 2, 3)

Key:
- TC
- TC
- TC

Temperature (at TCs 4, 5, 6)

Key:
- TC
- TC
- TC

Other Observations:

Burn pattern:
- 180 seconds

Dräger analysis:
- NO\textsubscript{x} 100 ppm
- HCN 90 ppm
- HCl ppm

Weight loss: 77%

X ... represents ignition point

Sample Reference: 251 (NFR-PVC)
Temperature (at TCs 1, 2, 3)  

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>TC 1</th>
<th>TC 2</th>
<th>TC 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>1</td>
<td>120</td>
<td>170</td>
<td>220</td>
</tr>
<tr>
<td>2</td>
<td>140</td>
<td>190</td>
<td>240</td>
</tr>
<tr>
<td>3</td>
<td>160</td>
<td>200</td>
<td>260</td>
</tr>
<tr>
<td>4</td>
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<td>210</td>
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</tr>
<tr>
<td>5</td>
<td>200</td>
<td>220</td>
<td>300</td>
</tr>
</tbody>
</table>

Temperature (at TCs 4, 5, 6)  

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>TC 4</th>
<th>TC 5</th>
<th>TC 6</th>
</tr>
</thead>
<tbody>
<tr>
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<td>100</td>
<td>150</td>
</tr>
<tr>
<td>1</td>
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<tr>
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</tr>
<tr>
<td>3</td>
<td>110</td>
<td>190</td>
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</tr>
<tr>
<td>4</td>
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</tr>
<tr>
<td>5</td>
<td>150</td>
<td>270</td>
<td>350</td>
</tr>
</tbody>
</table>

Smoke levels  

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Conc. Smoke (w.d.d.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>1</td>
<td>1.5</td>
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<td>3</td>
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<tr>
<td>5</td>
<td>3.5</td>
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</tbody>
</table>

CO levels  

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Conc. CO (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>1</td>
<td>750</td>
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<tr>
<td>2</td>
<td>1000</td>
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<tr>
<td>3</td>
<td>1250</td>
</tr>
<tr>
<td>4</td>
<td>1500</td>
</tr>
<tr>
<td>5</td>
<td>1750</td>
</tr>
</tbody>
</table>

Other Observations:  

- Burn pattern:  
- Dräger analysis:  
  - NO\textsubscript{x}: 0 ppm  
  - HCN: 0 ppm  
  - HCl: 0 ppm  
- Weight loss: \%

X ... represents ignition point.

Sample Reference: 252 MATCH
TEMPERATURES RECORDED AT THE CENTRE OF TEST PIECE
(subjected to smouldering test)

Graph 1.3.1: Smouldering Profiles of Cigarettes Alone

Graph 1.3.2: Smouldering Profiles of Varying Geometry of Initial Burn

Graph 1.3.3(a): Smouldering Profiles of Uncovered NFR

Graph 1.3.3(b): Smouldering Profiles of Uncovered NFR
TEMPERATURES RECORDED AT THE CENTRE OF TEST PIECE
(subjected to smouldering test)

Graph 1.3.3(a) : Smouldering Profiles Of Uncovered FR.

Key:
- FR Filter (Test Ref. 3.3)
- NR Filter (Test Ref. 3.0)
- H. Filter (Test Ref. 3.10)
- NR Filter (Test Ref. 3.4)

Note: As Self-Ignition Point

Graph 1.3.4(a) : Smouldering Profiles Of Covered NR.

Key:
- No Covering (Test Ref. 3.13)
- 5/A Covering (Test Ref. 3.14a)

Graph 1.3.4(b) : Smouldering Profiles Of Covered FR.

Key:
- No Covering (Test Ref. 3.13)
- 5/A Covering (Test Ref. 3.14a)
TEMPERATURES RECORDED AT THE CENTRE OF TEST PIECE
(subjected to smouldering test)
TEMPERATURES RECORDED AT THE CENTRE OF TEST PIECE
(subjected to smouldering test)

Graph 1.5.5a: Smouldering Profiles Of Uncovered NFR in Draught Conditions

Graph 1.5.5b: Smouldering Profiles Of Uncovered NFR in Draught Conditions

Graph 1.5.5c: Smouldering Profiles Of Uncovered NFR in Draught Conditions

Graph 1.5.5d: Smouldering Profiles Of Uncovered NFR in Draught Conditions

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A 2.3.2. Typical Thermograms Of Thermogravimetric Analysis Of Fabrics

Heating Rate: 50°C/min.
Starting Weight Of Sample: 20mg
Atmosphere: Air at 4000cfm

Temperature (°C)

Weight Loss (%)

Key:
- Wool
- Cotton/Acrylic
- Wool/Rayon
- Polyurethane
- PVC
- Names Foil
APPENDIX 3: PHOTOGRAPHS
PHOTOGRAPH A3.1: EXTERIOR VIEW OF FIRE TEST FACILITY.
APPENDIX 4 Measurement of 2,4 & 2,6 Tolylene Diisocyanate

A.4.1. Tetrachloroethylene SLR (TCE) was used as solvent, which had been carefully distilled at \(\sim 120^\circ C\) to remove traces of phenol. Pure phenyl isocyanate (~28.33 mg, i.e. equivalent 1 mg \(\equiv\) NCO in 10 ml TCE) was weighed out and dissolved in TCE (100 ml). The exact concentration of this solution was calculated and by a series of dilutions a series of solutions were obtained (125, 100, 50, 40, 25, 10, 5, 2, 1 and 0.5 ppm of \(\equiv\) NCO). The infra-red spectrum on slow scan in the range 2000 to 2600 cm\(^{-1}\) of these solutions was measured on a 'Unicam SP 200 G', with sodium chloride cells (1 mm path length), and TCE in the reference beam. A base line was drawn through the absorption minima at approximately 2,050 and 2,400 cm\(^{-1}\) and the absorbance of the solution determined for an absorption maximum at 2,258 cm\(^{-1}\). A calibration curve (Figure A4.1) of absorbance against isocyanate concentration was measured.

A.4.2. The combustion gases (9675 ml) in the sampling bottle were sampled. TCE (58 ml) was quickly added through the upper tap and then bottle shaken for five minutes to dissolve any isocyanate present. A portion of this solution was then run on the spectrometer using TCE as a reference and any isocyanate present was read off from the calibration curve.
**FIG A4.1: CALIBRATION CURVE FOR ISOCYANATE RADICAL FROM INFRA-RED QUANTITATIVE ANALYSIS.**
A.5.1. Setting Up of the Apparatus

The following procedure was followed:

(i) The smoke monitoring apparatus was turned on and allowed to equilibrate for at least 30 minutes. Then it was calibrated for 0 and 100% obscuration for the full-scale of the chart paper.

(ii) The window heater was connected up to the battery.

(iii) All sampling points were opened to the atmosphere and the sampling apparatus purged of extraneous gases for a minimum of 15 minutes at approximately 10 litres/minute.

(iv) The windows of the smoke monitoring apparatus were cleaned with solvent.

(v) The cold trap was filled with solid carbon dioxide and methanol.

(vi) The specimen was weighed and placed into the sample holder. This was then positioned above the eventual contact point of the flame tip. A thermocouple probe was, in some cases, inserted centrally into the rear of specimen. The ignitor was placed on the nozzle of the burner.

(vii) The door, sampling traps and exhaust vent were closed.

A.5.2. Operation During a Burn and Analysis

The following procedure was carried out:

(i) The temperatures of the five fixed thermocouples and the removable probe (when used) were recorded.
(ii) The flame was remotely ignited, the clock and chart recorder (running at 1 cm/minute) were started at the same time.

(iii) For the first 30 seconds of the test observations were made of the burn to ensure things were running smoothly.

(iv) The temperature of the chamber was recorded at regular intervals over a 60 seconds cycle.

(v) The gas was burnt for a fixed period and then stopped when the flame was apparently self-supporting in the specimen. Allowing for complete incineration where possible, the burn time of the specimen was noted. Once the flame was completely extinguished the airbrick was sealed by the rubber bungs to prevent external air mixing and diluting the smoke or letting the smoke escape.

(vi) The temperatures were followed beyond their peak values until they all dropped below 50°C, when the vacuum pump was turned on at ~ 10 litres/min to draw the air out of the sampling apparatus replacing it by material from the chamber, one of the sampling points having been opened to the chamber previously. The vacuum pump was run at this rate for a minute, and then reduced to less than 1 litre/min to facilitate sampling by Dräger. The Dräger tube was connected to the side arm of the sampling point by rubber tubing, a controlled volume of combustion gases were drawn through the tube by means of a hand pump to measure any of these gases: carbon monoxide, hydrogen cyanide, nitrogen oxides, TDI, oxygen and hydrogen chloride. The method of operation was indicated by Dräger technical instructions (CH 299 and CH 206, CH 257, CH 277, 67 00245, CH 316 respectively).
Once the colourmetric analysis was completed the sampling point was sealed and the rate of evacuation increased to 10 litres/min and gas samples were allowed to replace air in the sampling bottle for 90 to 120 seconds. Then the tap nearest the pump was shut, allowing the slight vacuum present in the bottle to draw gases from the chamber. It was then left for a time allowing atmospheric pressure to be reached, when it was assumed to be full of the sample only. The other tap was then closed, and the bottle removed for further analysis. The details of the TDI analysis are detailed in Appendix 4.

The recorder chart was stopped.

A.5.3. Post Burn Operations

In preparation of the next test the following was carried out:

(i) The exhaust system was turned on, the vent opened and the bungs removed from the airbrick so that the chamber could be purged of smoke and gases. This purge took a minimum of an hour, allowing the temperature to fall to ambient and the atmosphere to be totally cleared.

(ii) Once the pen on the chart recorder stopped falling towards 0% obscurcation, the chamber door was opened. The specimen holder and what remained of the specimen were removed. These were weighed. In a limited number of tests the foam left was washed to remove any absorbed polyol, dried and weighed. The polyol residues were washed away from the interior of the chamber. The protective windows of the smoke monitoring apparatus were cleaned, and the amount of solids deposited on them measured.

(iii) The rig was then ready to reuse.
APPENDIX 6: Calibration of Optics

A.6.1. Calibration of Neutral Optical Density Filters

From the BS 1384 test carried out by Kodak on the neutral optical density (NOD) filters, the following values were established:

<table>
<thead>
<tr>
<th>Originally Labelled (N.O.D.)</th>
<th>Calibrated to BS 1384</th>
<th>Actual Transmission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.11</td>
<td>78</td>
</tr>
<tr>
<td>0.2</td>
<td>0.19</td>
<td>65</td>
</tr>
<tr>
<td>0.3</td>
<td>0.30</td>
<td>50</td>
</tr>
<tr>
<td>0.5</td>
<td>0.51</td>
<td>31</td>
</tr>
<tr>
<td>0.7</td>
<td>0.72</td>
<td>19</td>
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<tr>
<td>1.0</td>
<td>0.98</td>
<td>10.5</td>
</tr>
<tr>
<td>2.0</td>
<td>1.97</td>
<td>1.07</td>
</tr>
</tbody>
</table>

The full visible spectral response of the neutral optical density filter were roughly checked on a "Unicam" SP 800 spectrometer, by placing each filter across the sample beam. The graph A.6.1. shows the typical response and is at a minimum at the mid-point of the visible spectrum, although there were some deviations from the Kodak results.

6.2. Construction of Millivoltage to Neutral Optical Density Conversion Table.

The basis of the table was to establish for a fixed output of light the MVs produced for neutral optical density equivalents of 0.00, 0.1, 0.3, 0.5, 0.7, 1.0 and 2.0. The process was repeated for different outputs of light. The lamp voltage was fixed at 28 volts, and the current through the filament was adjusted by the 5K \( \Omega \) pot. The current that produced maximum light output was 1.25 amps, and above this value the feedback circuit would not fully function. At 1.37 amps the reference photodetector became "swamped". Then by drawing the following graphs:
(i) for each light output (i.e., fixed amperage) neutral optical density v millivoltage (see Figure A.6.2(a)).

(ii) for each neutral optical density (including values extrapolated from Figure A.6.2(a)) millivoltage at a neutral optical density equivalent to 0.00 against millivoltage (see Figure A.6.2(b))

From the latter graphs a table of millivoltage to neutral optical density for any initial light value was constructed (see Table A.6.1.).
**FIG A6.1:** ABSORBANCE OF N.O.D. FILTERS.

**FIG A6.2 A&B:** CALIBRATION CURVES FOR SMOKE DETECTION APPARATUS.
### Table A.6.1

<table>
<thead>
<tr>
<th>Millivoltage (x 10^2)</th>
<th>Neutral Optical Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>0.15</td>
<td>0.15</td>
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<td>0.20</td>
<td>0.20</td>
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<tr>
<td>0.25</td>
<td>0.25</td>
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<tr>
<td>0.30</td>
<td>0.30</td>
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<td>0.35</td>
<td>0.35</td>
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<tr>
<td>0.40</td>
<td>0.40</td>
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<tr>
<td>0.45</td>
<td>0.45</td>
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<tr>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>0.55</td>
<td>0.55</td>
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<tr>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>0.65</td>
<td>0.65</td>
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<tr>
<td>0.70</td>
<td>0.70</td>
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<td>0.75</td>
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<td>0.80</td>
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<tr>
<td>2.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Note: The table shows the neutral optical density values for varying millivoltage levels.
<table>
<thead>
<tr>
<th>Millivoltage (x 10²)</th>
<th>Neutral Optical Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.10</td>
</tr>
<tr>
<td>0.15</td>
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<td>0.25</td>
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<td>1.70</td>
<td>1.80</td>
</tr>
<tr>
<td>1.90</td>
<td>2.00</td>
</tr>
</tbody>
</table>

**TABLE A.6.1. Conversion Tables - Millivoltage to Neutral Optical Density**

Contd......
APPENDIX 7: Operation of Present Test Rig.

The chamber at ambient temperature ($\sim 23^\circ$C) was cleaned of debris from the previous tests, particularly in the area of burn, also of soot from thermocouples and the observation windows in the door. The protective windows of the optics were thoroughly cleansed with methanol, and then the heaters were turned on for at least half an hour before test. The extraction trap was closed, the sampling tap opened, (for direct flow from the chamber to the sampling equipment), and the sampling pumps were turned on at a flow of 1.5 litres/minute.

The preconditioned, weighed sample was fixed into the sample holder, and carefully located on the floor of chamber, (to ensure positional repeatability); the relative positions from the walls and thermocouple TC1 were measured to ensure precise positioning. The ignition source (non-burning at this stage), was then placed in the desired position.

The flexible probe, inserted into the sample and connected to the 'Comark' thermometer, was used to ascertain fire spread or temperature at the centre of the fire. The interior lights of the chamber were turned off to prevent heating of the atmosphere (and thermocouples 4 and 5 in particular).

The IRGA 2B beam-chopper assembly was turned on and allowed to settle, (the infra-red lamp of the IRGA 2B remained permanently on to maintain the life of its filament). Once the IRGA had settled down it could be calibrated (at least once a month or after every 20 tests), according to the manufacturer's handbook (83), then after each test only zeroed (to be indicated by its own or the data logger's meter).

The lamp was adjusted to produce a voltage from the sample photodetector of 12 to 17 millivolts at 0.00 neutral optical density equivalent (i.e. 100% transmission). If this range was exceeded, any of the following...
could have occurred:

(i) the lamp may have its life drastically shortened
(ii) the reference photodetector will be swamped by the light and will not respond to any small changes of output
(iii) the sample photodetector may also be swamped to a lesser extent with loss of sensitivity in response.

Below the suggested range the following will occur:

(i) loss of response in the photodetector with the effective reduction of the 100 to 0% scale of transmission in terms of its millivoltage equivalent
(ii) interference of the sample photodetector response, if the flames from the fire become bright.

The cold junction of the thermocouple unit was filled with ice, and the cold traps with any desired coolant.

The data logger, having been turned on 15 minutes earlier to warm up, was set up for recording, ie:

(i) to read in order millivoltage from smoke, TC1, TC2, TC3, TC4, TC5, TC6, CO1, CO2 (and a spare line)
(ii) each line was checked to be operating. If a random millivoltage was indicated, the line was probably broken and had to be repaired
(iii) the data logger clock was corrected and started
(iv) the data logger/punch tape was set to read and indicate the time every 10 seconds (although a 5 second interval may be used with very rapid burns) and each item of millivoltage was read in the first 2.5 seconds of every 10 seconds segment
(v) the punch was set off to punch out tape.
A test could now be started. A suitable face mask (to prevent inhalation of any escaping fumes) was worn. The ignition source was lighted in situ and the stopwatch started. The observation door was carefully closed to minimise draughts. The burn was then observed and brief notes made where necessary (eg. indicating spread or nature of burn). A careful watch had to be kept to determine when the fire became extinguished, but this was difficult when thick smoke was present. If carbon monoxide reached levels greater than 0.4% a higher range (0 to 4% carbon monoxide) could be switched in, at the same time there had to be a switch from line 7 to line 8 on the punch tape. Once the fire was out the time was noted. The monitoring continued for two more minutes after the fire was apparently out to determine if smoldering was occurring or if flames had built up again. Once one was satisfied the fire was out, the post-fire tests could be carried out.

The atmosphere was sampled at the wall (by readjusting the sampling tap), for maximum levels of toxic gas using Dräger colourimetric tubes (at present particularly hydrogen cyanide and nitrogen oxides), following the instructions supplied with the tubes. Any sampling cold traps were removed for suitable analysis. Then the sampling tap was turned on so air from outside the chamber passed through the sampling equipment to purge the IRGA. The extraction trap was opened, and the extraction unit turned on. It has been found that a slight through-draught increased the efficiency of fume extraction achieved by slightly opening the observation door. The punch tape was turned off and the tape was processed. No computer programme had been designed for reading the punch tape, and calculating of results was carried out manually. It had been found convenient to read the tape on a
teleprinter and then translate the millivoltages on graphs for conversion to the desired monitored values. From the graphs the maximum values and rates of increased could be obtained.

Once the chamber was cleared of fumes, the sample was removed, reweighed and perhaps photographed or sketched; the next step could proceed. Times of turn round depended on the material burnt, and usually ranged from 30 to 90 minutes. It had been noted that six or so long duration tests could overheat the atmosphere of the chamber. Delays in testing could result while the temperature was allowed to drop to at least below 30°C and preferably to 23°C.
APPENDIX 8: Calibration of Ignition Gas Lines

A.8.1. Determination of True Flow Rates

The true flow rate (corrected) of the gas flows from the burner was measured on the rig shown in Figure A.8.1. This consisted of a short copper pipe (\(\frac{\frac{1}{2}}{2}\) inch internal diameter) with a 'Rotameter' flowmeter (calibrated for air) half way along its length, screwed on to the gas outlet at the floor of the chamber. By varying the flow of propane and air (each recorded for flow), a true combined value of flow at the gas exit was estimated. The graph shown in Figure A.8.2 resulted.

The delay between turning on the propane and air, and the gas reaching the exit (where it was ignited), was 1.05 minutes at a flow of 150cc/min.

A.8.2. Determination of Maximum Flame Temperature of the 7-way Burner

With the seven-way burner in position an approximate estimation of flamelet temperature was carried out. It was assumed the hottest flame could be achieved when:

\[
5 \text{O}_2 + \text{C}_3\text{H}_8 \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} + \Delta H \text{ combustion.}
\]

Assuming air contains 20.95% oxygen, the requirement to achieve a theoretically perfect combustion is 1 : 25 (Propane to Air by volume).

Therefore a range of gas ratios were examined, to determine the approximate flame temperature.

The flexible thermocouple was placed in one of the central flamelets at its hottest point as shown in Figure A.8.3. The first set of tests carried out were to establish the nature of the flamelets at various ratios with the results shown in Table A.8.1.
TABLE A.8.1.

<table>
<thead>
<tr>
<th>Uncorrected Flow (cc/min)</th>
<th>Propane</th>
<th>Air</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>150</td>
<td>2800</td>
<td>Flame out</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>2000</td>
<td>Flame out</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2600</td>
<td>Maximum flow to maintain flame</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1200</td>
<td>Smallest flame</td>
</tr>
</tbody>
</table>

There was some indication that with the slight pressure variations, (available from the air cylinder), there was no difference to flow rate or flame size. The tests were completed by the determining flamelet temperatures with the results shown in Table A.8.2.

TABLE A.8.2.

<table>
<thead>
<tr>
<th>Uncorrected Flow (cc/min)</th>
<th>Propane</th>
<th>Air</th>
<th>Ratio (by vol.)</th>
<th>Total Flow (Corrected) (cc/min)</th>
<th>Max. Temp (°C)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>150</td>
<td>1500</td>
<td>1:10.0</td>
<td>1400</td>
<td>940</td>
<td>Yellow Tip to Flame.</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1800</td>
<td>1:12.0</td>
<td>1700</td>
<td>950</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2000</td>
<td>1:13.3</td>
<td>1900</td>
<td>960</td>
<td>Near completely Blue Flame.</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2400</td>
<td>1:16.0</td>
<td>2300</td>
<td>965</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2500</td>
<td>1:16.6</td>
<td>2400</td>
<td>965</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2700</td>
<td>1:18.0</td>
<td>2575</td>
<td>985</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2800</td>
<td>1:18.6</td>
<td>2675</td>
<td>1000</td>
<td>Small Blue Flame.</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2900</td>
<td>1:19.3</td>
<td>2775</td>
<td>1010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>3000</td>
<td>1:20.0</td>
<td>2875</td>
<td>1025</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>3100</td>
<td>1:20.6</td>
<td>2975</td>
<td>---</td>
<td>Loss of Flame.</td>
</tr>
</tbody>
</table>
FIG. A8.1: APPARATUS USED TO MEASURE CORRECTED FUEL GAS FLOW RATE.

Flow Calibration Using Flowmeter 500 to 5000 scfm (Air At NTP).

FIG. A8.2: CORRECTION CURVE FOR FUEL GAS FLOW RATE.
FIG A8.3: LOCATION OF THERMOCOUPLE TO MEASURE MAXIMUM FLAME TEMPERATURE.

FIG A8.4: RANGE OF GAS FLAME SHAPES.
APPENDIX 2.

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