APPENDIX Bi

THE EXPERIMENTAL PROGRAMME CARRIED OUT AT CRE GROUP LTD.

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The Experimental Programme Carried out at CRE Group Ltd.

1. Introduction

Two separate experimental Programmes were carried out:-

a) The first was to determine the performance of the material of construction of two flues, one containing a number of liners made with high sand content and the other built with a more conventional composition liner made from high alumina cement and kiln burnt aggregate. Simultaneously the effect on liner wall temperature of operating with and without insulating backfill was investigated. Temperatures at the mid point of the joints (ie midway between the inside and outside face of the liner) and upon the outer face of the liner were measured. Test coupons of a variety of concretes of different composition were hung in the high temperature zone near the base of the flues. Two complete chimneys (A and B) were built within the laboratory and fired for 10 days, according to a "heavy-duty domestic firing cycle". The chimneys were fired with small multifuel stoves and the operating regime was as might be used in a small house without central heating. Whilst uncommon in towns, small but significant numbers of properties with such a heating arrangement remain in country districts.

b) The second was to investigate the temperatures reached during soot fires and the rate of rise of liner temperature, a further chimney (C) was constructed. This was a vertical assembly of flue liners supported by a steel joist.

This experimental Programme was carried out under tight budgetary constraints. The results were frequently at variance with expectations and not repeated; the contractor thus warns against excessive interpretation of/or extrapolation from the results.

2. The Determination of the Performance of Concrete Liners under Simulated Domestic Firing Conditions.

Two chimneys were constructed within the CRE Group Laboratory: it is considered most convenient to describe the details of the construction of each, the subsequent test programme and the results separately for each chimney.

2.1 CHIMNEY A

2.1.1 Details of Construction and Material Composition

This was built of 225mm ID round liners (260mm OD) by 250mm within a 600mm square (external dimension) chimney. This in turn was constructed from 100mm thick concrete blocks (Density 1850-2025kg/m^3) The gap between the chimney and block work was filled with a very weak cement/Light Expanded Concrete Aggregate (LECA) mixture, approximately 1/20. Care was taken that the surface of all of the LECA was well coated with cement paste.

Only a very limited number of flue liners with a high sand content (Labelled OPC/sand/PFAg) were available. These were placed at the lowest part of the flue where temperatures were highest and therefore they experienced the most arduous duty. The flue was made up of a series of different products:-

Lowest section	Liner No. 20-12	OPC/sand/PFAg Reference xxx
(This was the maximum number available)		
Middle section	Liner No. 11-7	OPC/Pumice
Top section	Liner No. 6-1	HAC/Pumice

The analysis of the three flue liners, is given in the main body of the report (GMRS 4760 Page 19 of 22). This analysis has been carried out by Geomaterials Research Services Ltd (GMRS Ltd); this laboratory employs LYTAG as a generic name for aggregate manufactured from the ash derived from coal fired power stations. It is not necessarily the product sold under this trade mark.

The chimney was fired with a typical multifuel stove (Villager Stove Model C), connected via a vertical 150mm vitreous enamel flue pipe approx 0.5m long.The particular design has a tall canopied top and a simple partial roof baffle. Photographs of the installation are given in Appendix Biii Fig 1.7 & 1.8.

The chimney was fully instrumented by means of Type K thermocouples. Those thermocouples labelled “J” were installed within joints, the tip being located midway between the inner and outer faces of the liner wall. Thermocouples labelled S were attached on the outside surface of the liner, adjacent to J. Thermocouple T/C 1 is located at the top of liner No.20, T/C No. 2 at the top of liner No 17 etc.

2.1.2 Experimental Work Programme

The experimental Programme was designed against the hypothesis that there would be relatively simple correlation between the performance of a range of concrete materials and the highest temperature reached. (In reality the situation was found to be considerably more complex).

The appliance was fired according to the following regime: Bituminous Coal, Anthracite and Wood were burnt separately. The time and weight of each refuel was recorded.

Day 1	Initial Cold Static Pressure Test was carried out using fan, gas volume meter and manometer Coal
0800hrs	Fire lit gently
1100hrs	Refuelled - operated at low output
1500hrs	Refuelled - operated at draft ½ output
2000hrs	Refuelled -left to operate at full output – the fire was not banked overnight
Day 2	Coal
0800hrs	Sprayed each flue with 995ml water (Equivalent to 25mm of rainfall) lit and left ash pit cover off
1000hrs	Refuelled when level low – operated at full output
1300hrs	Refuelled operated at full output Continued all day at full output
2000hrs	Refuelled and left at full output - the fire was not banked overnight
Day 3	Coal Operated as per Day 2

Day 4	Coal Operated as per Day 2
Day 5	Anthracite Operated as per Day 2
Day 6	Wood Sprayed with 995ml water Operated at maximum possible output Detailed procedure to be discussed
Day 7	Coal – modest misuse test Sprayed with 995ml water Lit and left ash pit cover off The condition of the appliance was closely monitored and the flue not allowed to exceed a dull red colour
Day 8	Coal/wood mixture – subsequently changed to coal only Operated as per Day 2
Day 9	Coal Operated as per Day 2
Day 10	Coal Operated as per Day 2
Day 11	Inspection
Day 12	Coal Operated in open fire mode i.e. with doors open and carried out gas firing test

A Final Cold Static Pressure Test was Carried Out

Samples of liner were submitted before and after the testwork to GMRS Ltd for analysis.

2.1.3 The Flue Gas Temperatures Given by the Multifuel Stove.

Details of temperature profiles for the flue gas are given in graphs B16-24 attached to this report. The testwork (summarised in the table overleaf) showed that temperatures of flue gases in the base of flues was highest when burning bituminous coal, (time averaged values up to 450°C, although typically nearer 400°C) this was higher than when burning anthracite (time averaged values about 400°C) or wood (time averaged values about 280°C(Chimney A), and 440°C (chimney B)). Peak flue gas temperature when burning bituminous coal reached 900°C, although this value was typically sustained for less than 5 minutes. Mean typical values shortly after refuel (ie whilst the coal was devolatilising to produce flammable tars and vapours) were 700°C to 750°C for 20 to 30 minutes. Typical temperatures after devolatisation (ie when principally coke remained) fell to 400 - 500°C. Peak gas temperatures with wood and anthracite were much lower. It was noted that when Bituminous coal and wood were burnt, flame entered the flue pipe.

CHIMNEY A - SUMMARY OF FIRING CONDITIONS AND TEMPERATURES REACHED

Day	Fuel	Firing Rate	Max. Gas Temp. (°C)	Max. Mid wall Temp. (°C)	Notes
1	Bituminous Coal	Low	600	220	
2	Bituminous Coal	High	800	410	
3	Bituminous Coal	High	800	350	
4	Bituminous Coal	High	850	425	
5	Anthracite	High	500	260	
6	Wood	High	550	280	
7	Bituminous Coal	Misuse	925	520	
8	Bituminous Coal	High	850	420	Subsequent to test a full inspection was carried out. The chimney had substantial external cracks up to 3mm wide up to a height of 1m above the base. No obvious internal cracks by inspection from the base using a torch.
9	Bituminous Coal	High	830	400	
10	Bituminous Coal	High	780	380	
11	-	-	-	-	CCTV inspection showed severe cracking (both vertical and at an angle) of liners 18 & 19 (Numbered from top down) and severe joint failure in this area. Sweeping with a fibre brush from the top did not dislodge any material and even at the cracks there was no evidence of surface discontinuities where a sweep's brush might dislodge material. The chimney passed a smoke clearance test but a test to BS6461 Part 1 with the top closed produced considerable smoke emission. The chimney would have required substantial repair to be regarded as "fit for purpose".
12	Bituminous Coal	(open fire)	-	-	
	Gas	33kW	1050	530	

The "Maximum gas temperature" was the highest flue gas temperature determined at the midpoint of the vitreous iron appliance flue pipe; a 1.5mm diameter thermocouple was used but no correction has been made for radiation loss effects; reported temperatures will tend to be lower than if measured with a suction pyrometer.

The "Maximum Midwall temperature" is the highest recorded temperature at the midpoint of the thickness of the liner wall; this was usually recorded by thermocouple J1.

2.1.4 Temperature Profiles Experienced By The Flue Liners

Details of temperature profiles for the liner walls are given in graphs B16-B24 attached to this report

The highest liner midpoint temperature (this is a point half way between the inner and outer faces of the liner) was 520°C (with bituminous coal, under misuse conditions). This was located at the top of the bottom liner. The maximum mid liner temperature experienced with natural gas at 1000°C was 530°C.

The mid-point thermocouple located at 972mm (T/C NoJ2) showed a maximum temperature of 390°C. There was some cracking but no gross loss of liner integrity above this point. It may be noted that this value is substantially above the maximum mid-point temperatures given even at the lowest thermocouple (T/C No.J1) by wood (280°C) and anthracite (250°C), and is broadly comparable to normal operation with bituminous coal (about 400°C).

Typical temperature gradients between the liner mid-point and outside surface were 50°C to 70°C, rising to 90°C, under the gas shock test at 1000°C. This differential is lower than for Chimney B because of the thermal insulation (LECA) between the liner and structural concrete blocks. As a result of this it was unlikely the inside surface even of the lowest liner significantly exceeded 600°C.

2.1.5 The Damage Found to the Individual Liners

The lowest four liners showed severe cracking (typically into 100mm square sections), but significant damage did not extend beyond about 1.4 metre up from the point of flue pipe entry (i.e. the base of the chimney). (For photograph of liner – Biii Fig 1.1)

Chimney A – Flue contained by LECA backfill inside 600mm blockwork stack							
Round							
No from top	No from btm	Height	Material	Comments	Ring	Inside	
1	20	4860	HAC/Pum	**No cracks**	Sharp	Soot	
2	19	4617	HAC/Pum	**No cracks**	Sharp	Soot	
3	18	4374	HAC/Pum	**No cracks**	Sharp	Soot	
4	17	4131	HAC/Pum	**No cracks**	Sharp	Soot	
5	16	3888	HAC/Pum	**No cracks**	Sharp	Soot	T/CNo 6
6	15	3645	HAC/Pum	**No cracks**	Sharp	Soot	
7	14	3402	OPC/Pum	**No cracks**	Sharp	Soot	
8	13	3159	OPC/Pum	**No cracks**	Sharp	Soot	T/CNo 5
9	12	2916	OPC/Pum	**No cracks**	Sharp	Soot	
10	11	2673	OPC/Pum	**No cracks**	Sharp	Soot	
11	10	2430	OPC/Pum	**No cracks**	Sharp	Soot	T/CNo 4
12	9	2187	OPC/s/PFAg	**No cracks**	Sharp	Soot	
13	8	1944	OPC/s/PFAg	**No cracks**	Duller	Soot	
14	7	1701	OPC/s/PFAg	**No cracks**	Duller	Soot	T/CNo 3
15	6	1458	OPC/s/PFAg	**Large tooth missing**		Half Soot	
16	5	1215	OPC/s/PFAg	**Fine vert cracks**		Clean	
✶17	4	972	OPC/s/PFAg	**Loss of integrity**		Clean	T/CNo 2
✶18	3	729	OPC/s/PFAg	**Loss of integrity**		Clean	
✶✶19	2	486	OPC/s/PFAg	**Loss of integrity**		Clean	
✶✶✶20	1	243	OPC/s/PFAg	**Severe cracks**		Clean	T/CNo 1
HAC/Pum = High Alumina Cement & Pumice							
OPC/Pum = Ordinary Portland Cement & Pumice							
OPC/s/PFAg = OPC/Sand/Fly Ash Aggregate i.e. a high sand content liner							
✶Part of liners 17 &18 could not be separated and were severely broken							
✶✶Liner 19 had cracked into 6 large pieces							
✶✶✶Liner 20 was heavily cracked in several directions & very weak							
T/C	**Indicates Thermocouple at top of liner**						
Ring	**Indicates the sound made by the liner when struck**						

The masonry concrete structure of the chimney suffered significant weakening and structural movement during the misuse test, resulting in a horizontal displacement of the external concrete blocks and a corresponding vertical crack of about 3mm positioned about 600 mm up from the base of the chimney. This has been attributed to the use of LECA, and the relatively large thermal expansion of the liner used. An increase in width of the liner of up to 1.2mm might be expected. The masonry would also experience the expansion of the LECA. This compares with an equivalent of 0.1 mm for some quartz-based pumice.

The HAC/Pumice liners used in the top section of the flue showed no change in the properties of the concrete (Liner No. 5 & 6)

The OPC/Pumice liners used in the middle section of the chimney showed evidence of only minor deterioration of the cement paste with only a small degree of micro-cracking concentrated on the inside face. Reddening of the iron particles in the aggregate showed that the liner had experienced temperatures in excess of 250-300C. (Liner No. 10 & 11)

The condition of the high sand content liner, used for the base section, (Liner No. 19) may be best described by quoting from the report by the concrete laboratory; thus it had "suffered a very high level of deterioration due to heating with high levels of macrocracking and fine cracking… The extent of the cracking is such that this sample has lost much of its original strength. The processes that have led to the development of cracking in this sample relate to shrinkage due to loss of water from uncarbonated cement paste and shrinkage due to loss of CO_2, particularly at the inner face of the liner where the paste is now uncarbonated". Immediately after the testwork, the liner could be crumbled by hand; although 10 weeks after the testwork, the chimney had regained some modest strength, particularly on the outside face.

2.1.6 The Chimney Leakage Rates

This is described together with data from Chimney B in Section 2.2.6 of this Appendix.

2.2 CHIMNEY B

2.2.1 Details of Construction and Material Composition

This was built of a 185mm square liners by 610mm high within a 400mm square chimney (external dimension). This was in turn constructed from 100mm thick concrete blocks. (Density 1850-2025 Kg/m^3) The small air gap between the chimney liner and block work was left empty except for the inevitable bridging by both flue liner sealant and mortar. The liners were all provided by the same company and were made from HAC/Kiln Burnt Aggregate (KBA). The analysis of these samples is given in Table 4 (GMRS 4760 Page 19 of 22). The wall thickness for this product (24 – 28 mm) was very slightly less than that used in conventional production (25 – 30 mm), but this would not be expected to alter the results, particularly the effect of temperature upon the integrity of the concrete at a microscopic level. Liner No 7 was typically 27mm thick.

All of the liners consisted of High alumina Cement and Kiln Burnt aggregate.
No backfill was utilised, the small air gap between the liner and concrete blocks was left air filled.

The analysis of the flue liner is given in Table 4 attached (GMRS 4760 Page 19 of 22)

The chimney was fired with the same equipment as used for Chimney A.

The Chimney was fully instrumented in the same fashion as used for Chimney A.

2.2.2 Experimental Work Programme

An identical Programme was used as for Chimney A. 885ml of water was sprayed down from the top of the chimney, to maintain an equivalent rainfall of 25mm.

2.2.3 The Flue Gas Temperatures Given by the Multifuel Stove.

These are reported in the attached graphs B27 to B37 and in the table overleaf. They are broadly similar to those found within Chimney A.

CHIMNEY B - SUMMARY OF FIRING CONDITIONS AND TEMPERATURES REACHED

Day	Fuel	Firing Rate	Max. Gas Temp. (°C)	Max. Mid wall Temp. (°C)	Notes
1	Bituminous Coal	Low	600	130	
2	Bituminous Coal	High	800	260	
3	Bituminous Coal	High	800	300	
4	Bituminous Coal	High	800	290	
5	Anthracite	High	630	200	
6	Wood	High	750	230	
7	Bituminous Coal	Misuse	900	390	
8	Bituminous Coal	High	820	260	Subsequent to test a full inspection was carried out. No obvious internal cracks by inspection from the base using a torch. No external cracks to the structure other than occasional hairlines in the mortar near the base.
9	Bituminous Coal	High	860	280	
10	Bituminous Coal	High	870	280	
11	-	-	-	-	CCTV inspection showed significant cracking (one vertical near a corner and two horizontal) of the lowest liner, no further external cracking. Sweeping with a fibre brush from the top did not dislodge any material, and even at the cracks there was no evidence of surface discontinuities where a sweep's brush might dislodge material. The chimney passed a smoke clearance test, but a test to BS6461 Part 1 with the top closed produced considerable smoke emission. Total smoke emission was substantially less than with Chimney A. The chimney would have required substantial repair to be regarded as "fit for purpose".
12	Bituminous Coal	(open fire)	-	-	
	Gas	33kW	1050	420	

The "Maximum gas temperature" was the highest flue gas temperature determined at the midpoint of the vitreous iron appliance flue pipe; a 1.5mm diameter thermocouple was used but no correction has been made for radiation loss effects; reported temperatures will tend to be lower than if measured with a suction pyrometer.

The "Maximum Midwall temperature" is the highest recorded temperature at the midpoint of the thickness of the liner wall; this was usually recorded by thermocouple J1.

2.2.4 Temperature Profiles Experienced by the Flue Liner

Details of temperature profiles for the flue gases and liner wall temperatures are given in graphs B27 to B37 attached to this report. The thermocouple recording liner midpoint temperature at 1200mm (T/C No J2) usually recorded a temperature above that at 610mm (T/C No J1). This is probably because T/C No.J1 was at a point of cold air inleakage. The lowest liner suffered three substantive horizontal cracks and one vertical crack in a corner. Maximum-recorded midpoint liner temperatures were 390°C. Obvious macro damage to the liners ceased about 1.2 m above the base of the chimney (i.e. in a broadly similar position to that of Chimney A). It may be noted that maximum mid point temperatures with wood were 280°C and anthracite were 250°C. The maximum midliner temperature experienced with gas at 1000°C was 420°C. This is about 30°C higher than with bituminous coal under misuse conditions. Typical temperature gradients between the liner mid-point and outside surface were 120°C to 160°C, rising to 190°C, under the gas fire test at 1000°C. This is greater temperature differential than seen across the liner of Chimney A and reflects the absence of thermal insulation, and the close proximity of the liner to the outer masonry blocks. This would be expected to place a greater thermal strain upon the liners. Maximum inside wall temperature is predicted to be about 550°C

2.2.5 The Damage Found To Have Occurred to the Individual

Chimney B Flue contained within 450 mm stack- no backfill							
Square							
No from top	No from btm	Height	Material	Comments	Ring	Inside	
1	8	4880	HAC/Lytag	No cracks	Sharp	Soot	
2	7	4270	HAC/Lytag	No cracks	Sharp	Soot	
3	6	3660	HAC/Lytag	No cracks	Sharp	Soot	T/CNo6
4	5	3050	HAC/Lytag	No cracks	Sharp	Soot	T/CNo5
5	4	2440	HAC/Lytag	No cracks	Sharp	Soot	T/CNo4
6	3	1830	HAC/Lytag	No cracks	Sharp	Soot in corners	T/CNo3
7	2	1220	HAC/Lytag	Cracks	Dull	Clean	T/CNo2
8	1	610	HAC/Lytag	Loss of integrity	Dull	Clean	T/CNo1
Liner numbers refer to numbering from top down							
Liner 7 had a horizontal crack causing loss of two large sections & a vertical corner crack							
Liner 8 had cracked horizontally & vertically at a corner							

The masonry concrete blocks forming the structure of the chimney showed no significant structural movement, only a few hairline cracks showing whilst under fire. The absence of cracks can be rationalised by the slightly lower liner temperatures, the higher temperature of the surrounding blocks and the smaller distance between the inside faces of the external masonry relative to the circular liner (250mm cf 400mm).

The condition of the concrete forming the topmost liner (Liner No. 1) was unchanged over the test Programme. The condition of the lowest liner (Liner No. 8) may be best described by quoting from the report by the concrete laboratory (for photograph of liner No 8 see Biii Fig 1.2); thus it had “deteriorated but slightly less than the 225mm round. The principal deterioration is cracking with obvious macro-cracking and fine cracking. There is network of very fine cracks that form a pattern of crazing at the inner surface (*this rendered the inside face extremely soft ie it could be scratched to a depth of about 0.5 mm with a small plastic rod).* The sample is weakened as a result of this cracking and can be broken by hand….the principal process that has led to much of the cracking is loss of moisture from uncarbonated cement hydrates and loss of moisture from uncarbonated calcium aluminate hydrates. Other contributory factors may include thermal shock and differential thermal movements in the structure." (See also Photograph Biii Fig 1.6). The HAC/KBA (Liner No. 7 & 8) although substantially cracked appeared to have kept much of its strength. It could only be broken by hand with difficulty. The inside face was very soft. There has been discussion as to whether any reduction in thickness of the liner below the 25mm standard could have significantly affected the result. As the majority of the liners exceeded 25mm thickness and as the principle damage to the liners was at the microscopic scale (ie the kind of damage that leads to softening of the inner face) any effect of such variation in wall thickness is not considered significant. Changing the liner thickness from 25 to (say even) 23mm is not considered to significantly alter the temperature of the inside liner wall.

2.2.6 Air Leakage Rates for Chimneys A & B

2.2.6.1 Leakage under Cold Static Conditions

The air leakage rates of Chimneys A & B were measured using a pressurising fan, gas volume meter and manometer. This was carried out before and after the testwork. This leakage rates were then corrected to 20Pa and 40Pa and expressed as $l/s/m^2$. The assumption has been made that air leakage is principally via fine tortuous paths, whereupon the leakage rate is directly proportional to pressure. If leakage were via a large orifice, leakage rate would be proportional to the square root of the pressure. The assumption adopted here thus may slightly overestimate leakage at higher pressures, but this approach is in line with other data. (BSRIA Interim Report on the testing of Masonry Chimneys, Contract 7562, Report No 1).

Corrected to	Chimney A $l/s/m^2$		Chimney B $l/s/m^2$		Leakage rate ratio Chimney A/B	
	Before	After	Before	After	Before	After
40Pa	2.15	16	0.24	5.07	9	3.2
20Pa	1.07	8	0.12	2.54		

prEN1857 maximum leakage rate N1 < 2.0 $l/s/m^2$ at 40 Pa
N2 < 3.0 $l/s/m^2$ at 20 Pa

2.2.6.2 Leakage under Hot Operational Conditions

Air leakage rates were also calculated via a mass balance upon the chimney from a measurement of fuel burning rate, and CO_2 concentration. CO_2 concentrations were measured at the top and bottom of the chimney. From this data, the estimated burning rate of the fuel, and its analysis the flue gas flow rate into the base of the flue is calculated in kg/hr. This calculation is repeated for the top of the chimney. The difference in mass flow rate (kg/hr) can only derive from air ingress. This mass flow rate can then be converted into air at 15°C to give a total volumetric inleakage. This method can be carried out with reasonable accuracy above a closed stove because of the high concentration of CO_2 (4 to 8%).

The experiment was performed over four successive periods, when the appliance was fired with bituminous coal. Numerical results are reported below Typical CO_2 values at the base and top of the flue for different periods were 7.3% down to 4.3%, and 3.7% down to 2.7% ie substantial falls indicate very substantial dilution (and hence chilling) of the flue gases.

Data Period	Chimney A m^3/hr	Chimney B m^3/hr
1	19.89	7.62
2	11.66	8.96
3	11.45	5.51
4	14.02	9.33
Average	**14.25**	**7.85**

Chimney A $l/s/m^2$	Chimney B $l/s/m^2$	Leakage Rate Ratio Chimney A/ B
1.61	0.59	2.74
0.94	0.69	1.37
0.93	0.42	2.18
1.13	0.72	1.58
1.15	**0.60**	**1.91**

2.2.6.3 Correlation Between Cold Static and Hot Operational Leakage Rates

No close numerical relationship is expected between the post test cold (Static) and Hot operational values. Under latter conditions an air inleakage of a “cold” jet via a large crack would be expected to behave differently to a pre-warmed gentle ingress via a series of fine microcracks. Nevertheless some general correlation might be expected between the relative leak rates of these chimneys under the two different conditions. This is indeed the case; thus the leak rate of Chimney A is approximately three times that of Chimney B under cold static conditions and approximately twice Chimney B under hot operational conditions.

2.3 TEST COUPONS WITHIN THE CHIMNEYS A AND B.

As part of the original contract is was agreed to place a variety of coupons of different composition within and near the base of chimneys A and B. The test results are in Appendix Biv.

The good performance of the simple OPC/sand mixture was not predicted. The unexpected nature of the results confirms the great difficulty with material based requirements within the Building regulations and indicate yet again that type testing against performance based specifications is the better way forward.

3 An Investigation of the Performance of Concrete Flue Liners during a Chimney Fire

3.1 CHIMNEY C

3.1.1 Details of Construction and Materials Composition

The chimney was built of 11 sections of round 225mm ID by 240mm high liners. The top half were made from HAC/Pumice, the lower half from OPC/Pumice. The liners were lightly restrained by a vertical steel joist. No outer blockwork was constructed. The centre section (approximately liners 4 to 8) was surrounded by 50mm thick insulating blanket. The inner surface was coated with an even mixture of 6mm of Bitumen Roof sealant made to "trowelling texture" with pulverised coal.

3.1.2 Experimental Work Programme

The fire was lit with a ring of fire lighters located at the base. After ignition the fire from the top (which lasted about 5 minutes) was not dissimilar to that seen from the top of many chimney fires. The fire emitted the usual roaring noise and the smoke was "Dark" rather than "Black". There was no evidence of the lining material melting before combustion; there were only occasional flakes of carbonised material failing from the flue. This is similar to a typical fire. In conclusion those present to witness the felt that it did represent a real fire. (Photographs are given in Appendix Biii Fig 1.3 & 1.4).

3.1.3 Temperature Profiles

Details of temperature profiles for the flue gases and liner wall temperatures are given in the graph B38 attached to this report. Thermocouples labelled J were installed at joints, the tip being located midway between the inner and outer faces of the liner wall. Thermocouples labelled S were attached on the outside surface of the liner, adjacent to J.

The graph of flue gas temperature and joint temperature shows the very rapid rate of temperature rise of the concrete itself when compared to normal use, This is estimated to be of the order of 100"C per minute. This is because of the radiant heat transfer within the chimney itself. This will subject any flue liner to extreme internal stresses. For comparison the rate of temperature rise of the first joint of Chimney A when burning bituminous coal was typically less than 5°C per minute and rarely above 10°C per minute.

3.1.4 The Damage Found to the Individual Liners

Chimney C Flue built in open air. Central section wrapped with insulating blanket							
Round							
No from top	No from btm	Height	Material	Comments	Inside	Insulation and position of Thermocouple	
1	11	2673	HAC/Pum	**Closed but signif.**	Soot	N	T/C no 3
2	10	2430	HAC/Pum	**Closed but signif.**	Soot	N	
3	9	2187	HAC/Pum	**No cracks**	Soot	N	
4	8	1944	HAC/Pum	**2 substantial cracks**	Soot	Y	
5	7	1701	HAC/Pum	**2 substantial cracks**	Soot	Y	
6	6	1458	OPC/Pum	**No cracks**	Soot	Y	T/C no 2
7	5	1215	OPC/Pum	**No cracks**	Soot	Y	
8	4	972	OPC/Pum	**No cracks**	Soot	Y	
9	3	729	OPC/Pum	**No cracks**	Soot	N	
10	2	486	OPC/Pum	**Vertical cracks**	Soot	N	
11	1	243	OPC/Pum	**Loss of integrity**	Soot	N	T/C No 1
Liner numbers refer to numbering from top down							
Liners 1 & 2 were crossed by a "closed" but significant long vertical crack **Liners 4 & 5 were crossed by 2 very substantial vertical cracks(1mm wide)** **Liner 5 had a substantial section missing (150mmX50mm, attached to No 6)**							
Liner 11 was broken by three vertical cracks & loss of a large section (125mmX180mm)							

Most of the liners showed substantial radial cracks probably arising from differential thermal expansion between the inside and outside faces. During the first 1 to 2 minutes after ignition cracks (up to 1mm wide and several centimetres long) could be both seen and heard to open up on the outside of the liner. These then closed as ignition approached 5 minutes and the thermal wave passed across the liner both in the vertical dimension (as the fire spread up the chimney), but more importantly also from the inside face of the liner to the outside. The rapid heating of the inside face will cause expansion of this zone; for a short time the outer zone remains cold. As concrete is strong in compresion and weak in tension this will cause cracking of the outside zone. These cracks occurred in both the HAC and OPC liners.