

Client Report:

INVESTIGATION INTO BURNING CHARACTERISTICS OF AN AIR CURTAIN BURNER

Client report number 207838

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Executive Summary

General background

This report describes a study of the use of a new incineration technique - the "Air Curtain Burner" (ACB) - as part of an assessment by DEFRA of the potential for ACB's to be used to dispose of cattle and as part of a Foot and Mouth disease (FMD) contingency plan.

An ACB comprises a steel container with an internal refractory lining, open at the top for loading fuel and with a "manifold" running along the top of one long edge which is designed to produce a high velocity air stream over the top of the open container (the "curtain") in addition to creating a swirling action within the container to assist efficient combustion.

The FRS (Fire and Risk Sciences Division) study was carried out over a two-week period in January 2002. In week 1, two days of burns, involving timber (pallets and logs) were carried out to determine the thermal and gaseous/particulate emission characteristics of the burner. In week 2, the burner was used to incinerate bovine carcasses over a further two-day period.

On the four "burn" days approximately 83 tonnes of timber were consumed, with thirty carcasses (approximately 16.1 tonnes) consumed over two days in week 2 (15 carcasses on each burn day). A daily burn typically lasted for approximately 8 hours. Although throughputs of over 15 bovine carcasses per day were achieved when the S-121 ACB was operated during the FMD outbreak, it was decided, due to operating time restraints and the need to collate accurate data, to restrict the trial to 15 carcasses per day.

The ACB was comprehensively instrumented with thermocouples to determine the temperature profiles below and above the air curtain, a gas sampling probe to determine a range of gaseous species both below and above the air curtain, and flow rate measurements both into and out of the burner using a "bi directional McCaffrey probe".

In addition, comprehensive video and stills photography were obtained, which involved the use of both conventional and thermal imaging techniques.

Results

Temperatures.

The thermocouple traces showed a spread of temperatures, which varied depending on their position within the burner, fuel loading events and the build up of ash/fuel on the floor of the burner. In particular, temperatures in the main burning zone below the air curtain, normally ranged between 600°C and 1000°C. Temperatures in the upper regions of the burner (but below the curtain) were consistently between 800°C and 1000°C, even during loading events. Sparks were emitted throughout the ACB operation, with additional flames above the air curtain, particularly during periods of heavy or excessive fuel loading.

Gas analysis.

In the "above air curtain" position, the absolute concentrations of CO₂ were relatively low, averaging about 5000 ppm with brief excursions to 10,000 ppm and to below 500 ppm. CO concentrations were very low - mostly below 200 ppm. Oxygen concentrations generally ranged between 20.9% and 19.7%. Concentrations of these three gases at any point in time conformed extremely well to the expected oxygen balance. The low concentrations of CO₂ and CO and the small depression of O₂ concentration from ambient (20.9%) was consistent with the relatively large dilutions with fresh air arising from the air curtain flow.

In the "below air curtain" position - i.e. in a combustion zone and with less dilution from the air curtain, the concentrations of CO and CO_2 could rise significantly with a corresponding drop in the measured O_2 concentration to preserve the oxygen balance.

Of more significance, in combustion efficiency terms, is the CO₂/CO ratio. The British Standards Organisation has published in BS 7899 Part 2, a table of "fire types" which are classified in terms of a small range of key parameters, including the CO₂/CO ratio as a measure of the combustion efficiency:

	Temperature (°C)		Oxygen	Fire Effluents	
Fire Stage or type		Hot layer	to fire (%)	Oxygen from fire (%)	CO ₂ /
1. Non-flaming					
a) Self-sustaining	450- 600	RTª	21	>20	1-5
 b) Oxidative pyrolysis from externally applied radiation 	300- 600	<50	21	>20	1-5
 Non-oxidative pyrolysis from externally applied radiation 	300- 600	<50	0	0	<5
2. Well Ventilated Flaming Where the fire size is small in relation to the size of the compartment, the flames are below the base of the hot layer and fire size is fuel controlled	>700	RT to 500	>15	5-21	>20 ^b
3. Less well Ventilated Flaming Where the fire size may be large in relation to the size of the compartment, the flames are partly above the base of the hot layer and fire size is ventilation controlled:					
a) Small vitiated fires in closed compartments	>700	RT to 500	<15	0-12	2-20
 b) Post-flashover fires in large or open compartments 	>700	500 to1000	<15	0-12	2-20

[&]quot; RT = room temperature.

^bMay be lower if the burning materials contain fire retardants. In order to determine whether flaming decomposition conditions in a particular apparatus fall into category 2 or category 3 it is

necessary to use a non-fire retarded reference material capable of efficient combustion. Above the air curtain this ratio was > 1000 - indicating extremely efficient combustion. The table above indicates that any ratio above 20 is generally indicative of "efficient combustion". Below the air curtain, the ratio could drop to <10, indicating partial/incomplete combustion at the measurement point.

The results from the "off line" measurements of hydrogen cyanide, oxides of nitrogen, hydrogen chloride and sulphur dioxide showed that in all cases the concentrations were below the minimum level of detection with the techniques used.

Flow measurements.

Generally, the measurements showed a linear flow rate out of the box along the side opposite the air curtain manifold, approaching 10 m/sec. with a flow into the box on the manifold side approaching 2 m/sec.

Video, thermal imaging and stills photography.

Three sets of video tapes have been supplied with this report. They represent:

- (i) "Fixed camera" footage, of normal video, viewing from above the ACB and framed to cover the entire burning area. The camera was operational throughout the entire study and provided the burner operators with a continuous view of combustion conditions inside the burner. At fixed points, as decided by DEFRA, a half-hour continuous videotape was recorded. The tapes in PAL VHS format are provided with this report.
- (ii) Thermal imaging footage with a similar viewpoint and recording periods to the conventional video imaging was used. A false colour temperature zone technique has been applied to support the temperature measurements obtained from thermocouples.
- (iii) A "roving" video record was obtained, covering most of the operations associated with the study.

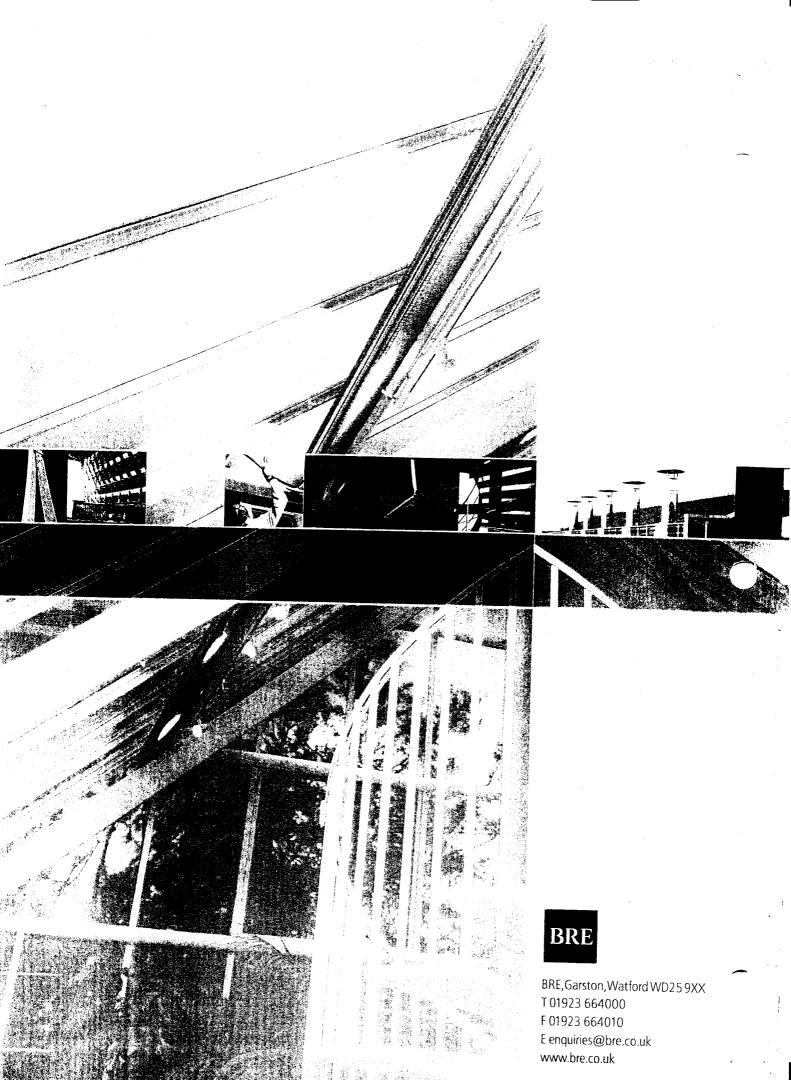
Stills photographs were taken at a number of locations around the test site to cover most of the operations. These are provided separately with this report.

Summary of general conclusions

- 1. When operated under the controlled conditions at Cardington (e.g. free from wind and precipitation effects) the ACB consistently produced internal temperatures of between 600°C and 1000°C (+).
- 2. When incinerating bovine carcasses, an average throughput of approximately 2 bovines (1.1 tonnes) per hour was achieved (taking into account the additional start up and shut down time required for 2 days burning). The incineration rates varied between the two carcass burn days. 49 tonnes of timber were consumed



- during the incineration of the bovine carcasses with a further 34 tonnes consumed during the two initial timber only burn days.
- 3. Measured emissions of carbon dioxide, carbon monoxide and oxygen from the burner box showed that large dilutions with air were present before products were released into the general atmosphere.
- 4. The calculated carbon dioxide to carbon monoxide ratio indicated, that based on BSI guidelines published in BS 7899 part 2, in the majority of the trials, highly efficient combustion was occurring prior to products being released into the atmosphere.
- Measurements of hydrogen cyanide, oxides of nitrogen, hydrogen chloride and sulphur dioxide showed concentrations below the minimum detection level for the sampling and analysis techniques used.
- 6. Sparks with a linear velocity of approximately 10m/sec were emitted, particularly with each fresh addition of fuel. Flames above the burner top were also in evidence at these times.



Introduction

During the foot and mouth outbreak of 2001, the disposal of infected carcasses and those produced by contiguous culls was a key requirement in the efforts to control and stop the spread of the disease. Cremation was chosen as a major route for carcass disposal and often took the form of large pyres in farm fields with a mixture of fuels such as railway sleepers, pallets logs etc. Kerosene fuel was commonly used to assist the combustion. The technique gave cause for some public concerns over the potential for such pyres to contaminate the atmosphere and the ground with toxic products. During the latter period of the incineration programme, a relatively new technique using an "Air Curtain Burner" (ACB) was used at a limited number of sites. The ACB is essentially a large rectangular "container"- like box with a refractory lining on the inner walls. A high velocity stream of air is blown across the full width of the top of the box from a "manifold" running along the top edge of one long side. The air supply is generated by an integral diesel engine coupled to a large capacity blower.

In operation, a fire is established in the base of the firebox using such timber waste as pallets and logs. Diesel fuel is used to assist the initial fire. The air supply via the manifold is then established and has two main functions. Firstly, it generates highly turbulent swirling conditions around the burning fuel assisting efficient (and therefore "clean") combustion. Secondly, it establishes a "curtain" above the firebox effectively "trapping" and recycling combustion products through the fire zone and providing a large diluting effect for combustion products released from the ACB. Approximately one hour after ignition of the fire, the ACB is ready to incinerate carcasses.

An end point is reached when the ash build-up reaches approximately 1m in depth (after approximately 24 hours of continuous incineration). Then, if necessary the ACB can be simply pulled to a fresh area and operations can continue.

The potential advantages of this system therefore include:

- Operation at the site of culling, preventing spread of disease during transportation of infected carcasses.
- Low gaseous emissions into the atmosphere,
- Low land contamination potential from the residual ash,

DEFRA therefore asked FRS/BRE to investigate the performance of an ACB under the controlled conditions available at Cardington. DEFRA arranged for analysis of the ash samples independently.

Description of the project

General

The Air Curtain Burner (ACB) used in this trial was manufactured in Florida USA by Air Burners LLC. The Chief Executive of Air Burners LLC (Brian O'Conner) was present throughout the trials.

The ACB was operated by Palleg Refuse and Recycling Limited of Ystradygynlais, South Wales UK, led by John Adams.

The FRS team comprised Peter Fardell, Norman Marshall, Phil Clark, with BRE support from Sue Rogers (Cardington) and Steve Gordon (Audio-visual).

The ACB was set up and operated adjacent to the steel framed building at Cardington, in a controlled environment, free from the effects of wind and precipitation.

Over 100 tonnes of timber (wooden pallets and logs) were stored at the Cardington site prior to the trials, with the controlled delivery of 30 bovine carcasses over two days in week 2.

The study was carried out over a two-week period. In week 1, only timber was combusted over two days. In week 2, 30 bovine carcasses were consumed over a further two-day period. A diagram of the ACB and a photograph of the ACB in operation are shown in figures 1 and 2 (below).

Figure 1 - Diagram of the ACB

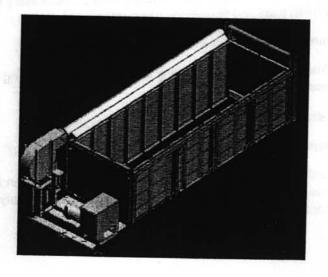
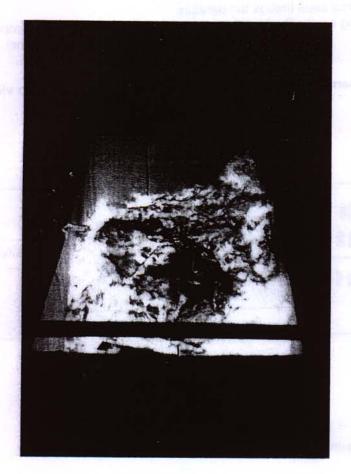


Figure 2 - Photograph of the ACB in operation following addition of a bovine carcass.



The overall dimensions of the firebox are 9.8m long, 3.78m wide and 3.13m high.

The air manifold is on the right hand side of figure 2 at the top of the burner box.

The gas-sampling probe can be seen in position below the air curtain.

Details of the measurements and instrumentation used are given below:

Temperatures:

All temperatures were measured using stainless steel sheathed chromel alumel thermocouples (1.0mm OD, 0.5mm type "K").

Thermocouple positions were as follows:

- 1-18 Projecting 20 mm into the fire box. (See figure 3 below).
- Steel building temperature (an adjacent building to the test site, monitored for safety reasons)
- 20 Ambient temperature (Measured at logging station)

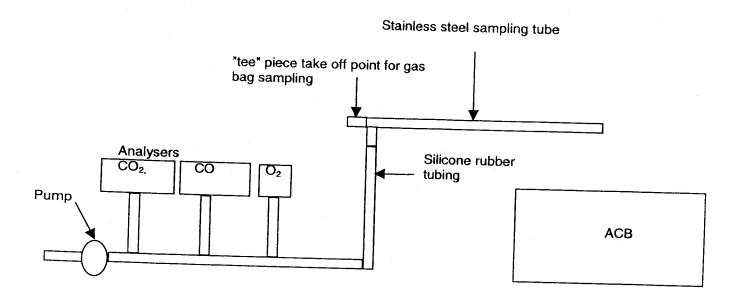
TABLE 1. DETAILS OF THERMOCOUPLE POSITIONS AND USE

Thermocouple number	Position from door end of ACB (mm)	Depth from top of ACB (mm)	Measurement	
1	140	91	ACB internal wall	
2	290	153	ACB internal wall	
3	290	94	ACB internal wall	
4	290	153	ACB internal wall	
5	500	91	ACB internal wall	
6	610	36	ACB internal wall	
7	510	89	ACB internal wall	
8	415	36	ACB internal wall	
9	355	209	ACB internal wall	
10	355	150	ACB internal wall	
11	355	87	ACB internal wall	
12	355	24	ACB internal wall	
13	323	88	ACB internal wall	
14	215	39	ACB internal wall	
15	140	88	ACB internal wall	
16	46	38	ACB internal wall	
17	Vertical centre line	58	Door 1	
18	Vertical centre line	92	Door 2	
19	•	-	Steel building	
20	-		Ambient temp.	
21	45	_	ACB External wall	
22	50	Above air curtain	Across burner	
23	50	Above air curtain	Across burner	
24	50	Above air curtain	Across burner Across burner	
25	50	Above air curtain	Across burner Across burner	

Gas analysis.

Sampling

Figure 5 - Schematic of the sampling system



A main sampling line was used, which consisted of a stainless steel tube, 5.5mm internal diameter and 5m long. This was suspended above the central portion of the burner and positioned approximately 1.5m above the top of the ACB, with the capability of being positioned at any point across the width of the burner. A length of flexible silicone rubber tubing was attached to the stainless steel tubing, and connected to a diaphragm pump used to extract the fire gases at a rate in excess of 5 litres/minute. Tee pieces were fitted just prior to the pump to supply continuous carbon dioxide, carbon monoxide and oxygen analysers, which were all fitted with smaller internal sampling pumps.

For the sampling of other gases which were to be analysed "offline" (hydrogen cyanide and oxides of nitrogen), a tee piece was fitted immediately after the stainless steel section allowing collection in 10 litre "Tedlar" gas sampling bag. A separate "in line" pump was used for this sampling with the main sampling line temporarily shut off, diverting all gases into the Tedlar bag. Pipe runs were kept as short as possible to minimise losses.

At the suggestion of the Environment Agency, immediately prior to the study, additional gases were included for analysis. These were hydrogen chloride (an indicator for dioxins) and sulphur dioxide. Sulphur dioxide and dioxins are gases commonly emitted when animal carcasses are burnt. In using hydrogen chloride as a surrogate for dioxins care must be exercised in interpreting the results. It has been established that in some

cases dioxin can be destroyed by exposure to high incinerator temperatures for a prescribed time, but is capable of reforming again. Therefore it is possible that in some thermal decomposition conditions, absence of hydrogen chloride may not necessarily mean absence of dioxin. This aspect needs further study.

Unfortunately the late decision to include these other gases left insufficient time to set up additional and more appropriate sampling methods for these gases and the same set-up was used for all gases.

It has to be accepted that losses in the sampling line through condensation, water solubility etc. with these additional gases are likely to be greater than for hydrogen cyanide and oxides of nitrogen. With these latter two gases, FRS experience shows that they suffer relatively small sampling losses in this type of sampling arrangement.

The main sampling line was not heated separately from the heating produced by insertion into the hot gas stream emerging from the burner. Experience in other work at FRS has shown that for carbon dioxide, carbon monoxide and oxygen measurements, a heated sampling line over this distance is not necessary and conducted heat maintained all chemical species of interest in the vapour phase up to the analysis points.

The use of chemical colour change aspirated tubes for gas analysis in fires is usually questionable on two main grounds:

- (i) The time taken to achieve a sample is long compared to the fire duration.
- (ii) A colour change may also arise through compounds present in addition to the compound being measured- so called "cross sensitivity".

However, the use of such tubes was considered justified in these tests, as the tests had long "steady state" periods and the gases measured were relatively free (as quoted in the manufacturer's data) from interfering compounds.

Gas analysis.

Carbon dioxide and carbon monoxide were monitored continuously using non-dispersive infra red analysers. Oxygen was monitored continuously using an instrument operating on the paramagnetic principle.

Other gases of interest - hydrogen cyanide, hydrogen chloride, sulphur dioxide and oxides of nitrogen were measured "off line" using chemical colour change aspirated tubes. (See "sampling" for a note on this).

Flow measurements.

Gas flows in and out of the ACB were measured using "bi-directional" or "McCaffrey" probes. These probes consist of a thin walled steel cylinder, 10mm diameter and 20 mm long with an internal central steel wall or membrane, positioned normal to the walls of the cylinder. The two "compartments" so formed are connected via steel tubes to a micromanometer and the pressure differential across the membrane is continuously measured when the cylinder is placed in line with the gas stream to be measured. The pressure

differential is directly related to the flow rate and the instrument is calibrated using a wind tunnel.

Although two such probes were originally installed (one each side of the burner box), only one was operational most of the time. This was therefore physically moved from one side of the box to the other at appropriate points in the trials.

Data logging

All temperatures and gas concentration data were logged continuously throughout each day of the study. A scan rate of one reading every 10 seconds was used.

Video imaging.

A thermal imaging camera was set up to view directly into the burner from above together with a conventional video camera. A third video camera was used to provide "roving" shots of the various operations involved in the study.

Moisture content of timber fuels

A number of moisture content measurements on the timber used as fuel were made on each day of the trials, using a proprietary "Protimeter" probe.

Findings

General

The study showed the advantages of operation in a controlled laboratory environment, free from the effects of wind and precipitation. The two trials involving only wood fuels in week 1, began between 10:30 and 11:00 and continued for approximately 6 hours. The two trials involving animal carcasses started at appoximnately 08:00 and continued for over 10 hours.

During the "steady state" periods of the trials, the visual emissions from the top of the ACB were confined to a small number of sparks emitted at approximately 10m/sec. With the addition of fuel, the concentration of sparks rose significantly and flames were apparent above the air curtain.

Table 2. Shows typical moisture content of the fuels burned.

Table 2. Moisture Content of fuels Burned during ACB trials.

Test Date	Fuel Type	Moisture content %		
23/01/02	Pallets	15 to 19		
23/01/02	Logs	14 to 28		
24/01/02	Pallets	17 to 22		
24/01/02	Logs	17 to 24		
29/01/02	Pallets	15 to 19		
29/01/02	Logs	17 to 22		

The companion video set to this report shows the general operation of the ACB at all stages and events associated with the trials.

The detailed results from this study are presented in four Appendices to this report, each representing one of the four "burn" days of the study. Please see figure 3 for a schematic showing the thermocouple positions.

Appendix A - Wednesday 23rd January 2002 - Timber burns only (mainly pallets).

Appendix B - Thursday 24th January 2002 - Timber burns only (mixed pallets and logs).

Appendix C - Tuesday 29th January 2002 - Timber and carcass burns

Appendix D - Wednesday 30th January - Timber and carcass burns

Each Appendix presents in turn:

Plots of temperatures where available over 6 charts: thermocouples 1-5, 6-8, 9-12, 13-16, 17-18, 22-25.

Plots of the continuous gas analysis of carbon dioxide, carbon monoxide and oxygen where available.

A plot of the air velocity into and out of the fire box.

In the case of the trials on the 23rd and 29th of January, there is a plot showing temperature changes over a narrower selected time period to illustrate the effect of fuel/carcass loading etc.

In terms of findings, this report is intended to provide a relatively brief summary of the main key features of the data collected during the study. It is recognised that DEFRA may well wish to examine the data in more detail subsequent to this report. FRS will be pleased to assist in this regard, if required, under a separate contractual arrangement. Details of the type of wooden fuel (i.e. pallets and logs) and loading times, and the details of the carcasses have not been recorded in this report. DEFRA personnel were responsible for this aspect of the work.

Wednesday January 23rd. (Wood-only burns)

Temperatures.

Generally temperatures were in the band 600°C to 1000°C. Exceptions were positions 1 and 2. These were situated on the opposite side to the air manifold with position 1 effectively directly in line with the air jet, and position 2 above the air curtain.

Temperatures above the air curtain were in the approximate range 200°C to 500°C, consistent with the cooling effect of the air curtain jet.

Gas analysis

Carbon monoxide concentrations were generally below 100ppm but with a transient peak of 5000 ppm at roughly the mid point of the day's trial. This corresponded with higher carbon dioxide concentrations (19,000 ppm maximum) at that point. Carbon dioxide concentrations were generally below 10,000 ppm. Although the theoretical yields of these gases have not been calculated, it is evident that the absolute concentrations are very low due to substantial dilution from the air curtain. The CO₂/CO ratio is also high (normally > 1000) indicating efficient (i.e. "well oxygenated") combustion using the criteria presented in BSI BS 7899 part 2 table 8.

Concentrations of the gases measured "off line" were all below the minimum detection level for this sampling and analysis methodology. Minimum detection levels were as follows:

Gas	Minimum detection level (ppm)
Hydrogen cyanide	2
Oxides of nitrogen	20
Hydrogen chloride	1
Sulphur dioxide	20

Air flows

The airflows were measured on the manifold side of the firebox and showed an initial out flow from the box of between 1 and 1.5 m/sec, for the first hour. From the point where the speed of the fan was increased and the velocity of the air curtain reached its maximum, an inflow into the firebox was observed, reaching a maximum of 2.5 m/sec.

Fuel loading events and temperature records.

A plot of the temperature recorded by thermocouple 12 and the loading of fuel on an expanded time scale is shown as the last diagram in Appendix A. This does appear to show some correlation of a dip in temperature with a loading event, but is provided mainly to demonstrate the possibilities of further analysis of this aspect if required.

Thursday January 24th (Wood-only burns)

Generally temperatures were in the band 600°C to 1000°C. Exceptions were positions 1 and 2. These were situated on the opposite side to the air manifold with position 1 effectively directly in line with the air jet, and position 2 above the air curtain. Thermocouple 9 registered between 400°C and 600°C for most of this trial and was probably due to the junction being immersed in ash and partially insulated from the main firebox environment.

Temperatures above the air curtain were in the approximate range 400°C to 800°C, consistent with the cooling effect of the air curtain jet. Some of the peak values seen were due to the thermocouple array being knocked into the flaming region of the burner, so therefore were measuring the temperatures below the air curtain.

Gas analysis

Carbon monoxide concentrations were generally below 100ppm but with a transient peak of 13,000 ppm towards the end of the day's trial. This corresponded with higher carbon dioxide concentrations (4%-5%) at that point with an oxygen concentration of approximately 17.5%. This occurred when the gas sampling probe was knocked below the air curtain and sampled the fire box atmosphere below the curtain. The "oxygen balance" - i.e. a summation of carbon dioxide concentration, half the carbon monoxide concentration and the residual oxygen concentration should approximate to the total available oxygen concentration (i.e. ambient) of 21%. At this point in the trial, the balance achieved was broadly correct, giving added confidence to the correct operation of the sampling and measurement system. Carbon dioxide concentrations were generally below 10,000 ppm.

Although the theoretical yields of these gases has not been calculated it is evident that the absolute concentrations are very low (apart from the episode described above) due to substantial dilution from the air curtain. The CO_2/CO ratio was also high (normally > 1000) indicating efficient (i.e. "well oxygenated") combustion using the criteria presented in BSI BS 7899 part 2 table 8.

Concentrations of the gases measured "off line" were all below the minimum detection level for this sampling and analysis methodology. Minimum detection levels were as follows:

Gas	Minimum detection level (ppm)
Hydrogen cyanide	2
Oxides of nitrogen	20
Hydrogen chloride	1
Sulphur dioxide	20

Air flows

The measurement points were alternated between the opposite manifold and the manifold side and showed the airflow out of the box on the opposite manifold side to be approximately 6 -10 m/sec, with the flow into the box on the manifold side approximately 1m/sec.

Tuesday 29th January (wood, plus 15 carcass burns)

Temperatures

Generally temperatures were in the band 400°C to 1000°C. Exceptions were positions 1 and 2. These were situated on the opposite side to the air manifold with position 1 effectively directly in line with the air jet, and position 2 above the air curtain. Depressions in temperature appeared to coincide with addition of carcasses but the general range remained in this approximate band. Thermocouple 9 again appeared "insulated" from the general fire box environment which was probably due to the junction being immersed in ash and partially insulated from the main firebox environment.

Temperatures above the air curtain (three operational thermocouples) were in the approximate range 400°C to 500°C, consistent with the cooling effect of the air curtain jet. Between the approximate times, 13:12 and 15:56, temperatures rose substantially, peaking occasionally to above 1000°C, due to the thermocouples becoming lowered into the firebox below the air curtain.

Gas analysis

No carbon monoxide concentrations were plotted for this trial. The measuring instrument showed "baseline" concentrations throughout the trial with only very brief excursions to a steady reading; these being below 100ppm, (full-scale range was 500ppm). Carbon dioxide concentrations were generally below 10,000ppm with transient peaks of 10,000 to 20,000ppm and the very occasional excursion above this. The "oxygen balance" - i.e. a summation of carbon dioxide concentration, half the carbon monoxide concentration and the residual oxygen concentration - should approximate to the total available oxygen concentration (i.e. ambient) of 21%. The oxygen balance again proved broadly correct, giving added confidence that the operation of the sampling and measurement system was valid. Although the theoretical yields of these gases have not been calculated, it is evident that the absolute concentrations are very low (apart from the episodes described above) due to substantial dilution from the air curtain. The CO₂/CO ratio was also high (normally > 1000) indicating efficient (i.e. "well oxygenated") combustion using the criteria presented in BSI BS 7899 part 2 table 8.

Concentrations of the gases measured "off line" were all below the minimum detection level for this sampling and analysis methodology. Minimum detection levels were as follows:

Gas	Minimum detection level (ppm)			
Hydrogen cyanide	2			
Oxides of nitrogen	20			
Hydrogen chloride	1			
Sulphur dioxide	20			

Air flows

These again generally showed the airflow rate out of the box on the opposite manifold side, of approximately 5-10 m/sec. A period of unstable readings was observed approximately half way through the day, this being due to damage occurring to the probe (caused by excessive flame impingement on to the probe).

Wednesday 30th January (wood, plus 15 carcass burns)

Temperatures

Generally temperatures were in the band 600°C to 1000°C. Exceptions were positions 1 2 and 4. These were situated on the opposite side to the air manifold with position 1 effectively directly in line with the air jet, and position 2 above the air curtain. Position 4 followed position 1 in recording much reduced temperatures (approx. 90°C) over a three hour period during the burn. Position 7 also showed lower temperatures (dropping to 250°C) approximately half way into the trial. The cause of these temperature reductions is not clear but could be due to the insulating effect of ash and other debris build up in the vicinity of the thermocouples. Depressions in temperature also appeared to coincide with addition of carcasses but the generally the range remained in this approximate band. Thermocouple 9 again appeared "insulated" from the general fire box environment which was probably due to the junction being immersed in ash and partially insulated form the main firebox environment.

Only two of the thermocouples strung across the top of the firebox were operational for this trial and one of these malfunctioned after about a third of the trial period had been accomplished. This and the remaining thermocouple showed the typical trend observed on the other days' trials, (i.e. temperatures of between approximately 200°C and 400°C showing the substantial cooling effect of the air curtain).

Gas analysis

No carbon monoxide concentrations were plotted for this trial. The measuring instrument showed "baseline" concentrations throughout the trial with only very brief excursions to a steady reading; these being below 100ppm. (Full-scale range was 500ppm). Carbon dioxide concentrations were generally below 10,000 ppm with transient peaks of 10,000 to 20,000 ppm and the very occasional excursion above this. The "oxygen balance" - i.e. a summation of carbon dioxide concentration, half the carbon monoxide concentration and the residual oxygen concentration - should approximate to the total available oxygen concentration (i.e. ambient) of 21%. The oxygen balance again proved broadly correct, giving added confidence that operation of the sampling and measurement system was correct. Although the theoretical yields of these gases have not been calculated it is evident that the absolute concentrations are very low (apart from the episodes described

above) due to substantial dilution from the air curtain. The CO_2/CO ratio was also high (normally > 1000) indicating efficient (i.e. "well oxygenated") combustion using the criteria presented in BS 7899 part 2 table 8.

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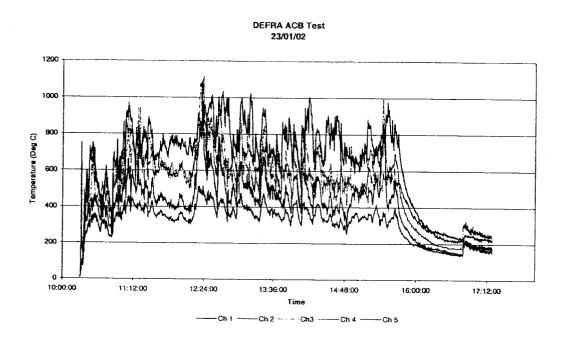
Air flows

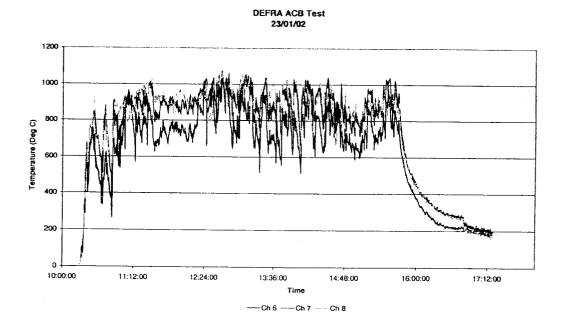
These generally showed the airflow rate out of the box on the opposite manifold side of approximately 5-10 m/sec.

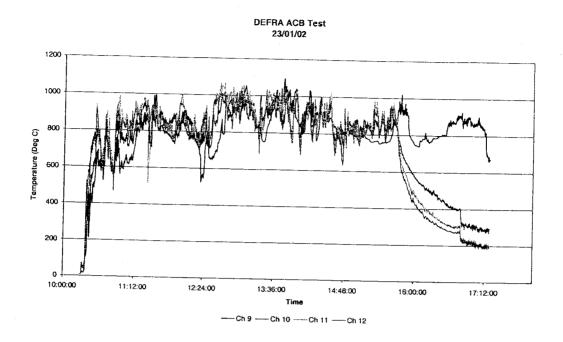
Conclusion and recommendations

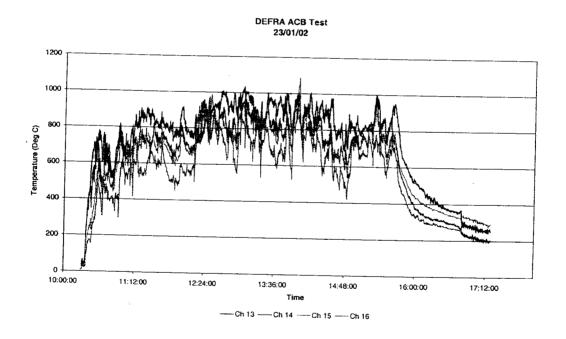
- When operated under the controlled conditions at Cardington (e.g. free from wind and precipitation effects) the ACB consistently produced internal temperatures of between 600°C and >1000°C.
- Approximately 83 tonnes of timber were consumed over the four days of burns and 30 bovine carcasses during two days of burns. All burns were of approximately 8 hours duration on each day.
- Measured emissions of carbon dioxide, carbon monoxide and oxygen from the burner box showed that large dilutions with air were present before products were released into the general atmosphere.
- 4. The calculated carbon dioxide to carbon monoxide ratio indicated that based on guidelines published in BS 7899 Part 2, at most stages during operation of the ACB, highly efficient combustion was occurring prior to products being released into the atmosphere.
- Measurements of hydrogen cyanide, oxides of nitrogen, hydrogen chloride and sulphur dioxide showed concentrations below the minimum detection level for the sampling and analysis techniques used consistent with efficient combustion.
- Sparks with a linear velocity of approximately 10m/sec were emitted, particularly with each fresh addition of fuel. Flames above the burner top were also in evidence at these times.

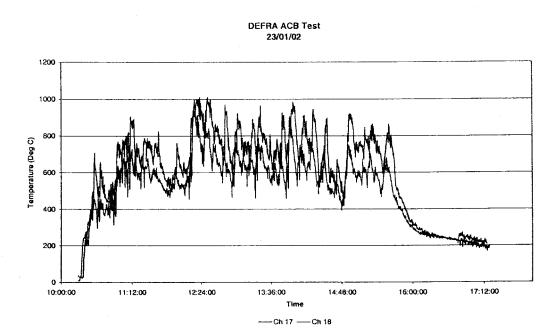
Appendix A. Results from the burns on Wednesday 23rd January 2002

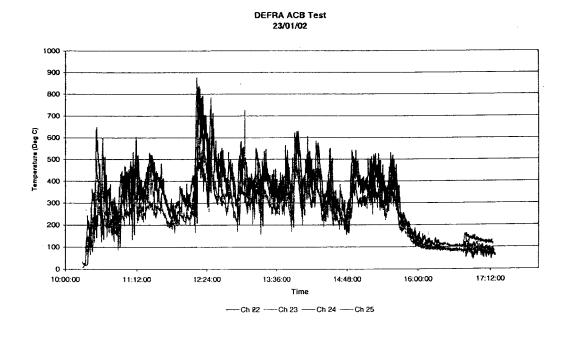


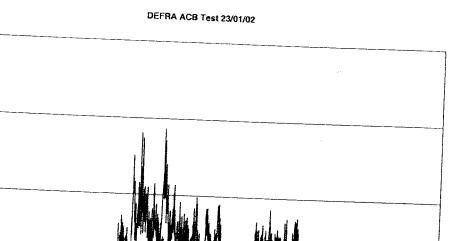










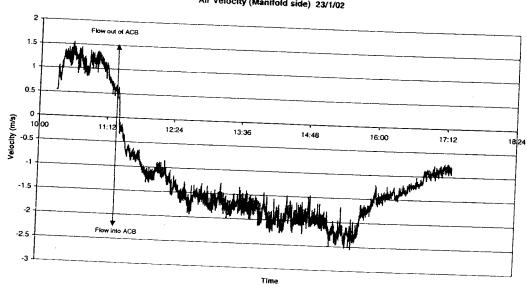


16:00:00

17:12:00



-- CO2 %. --- CO %



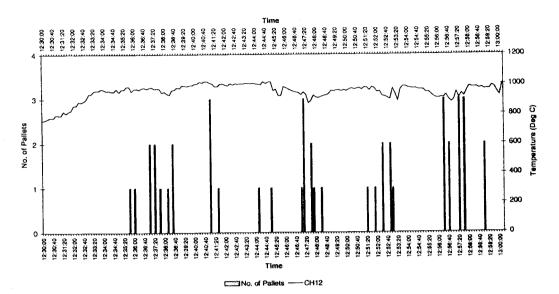
Concentration (%)

10:00:00

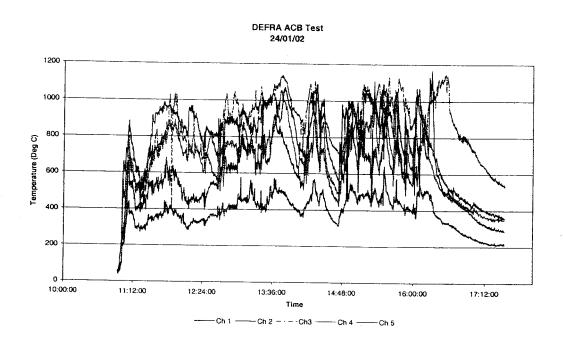
11:12:00

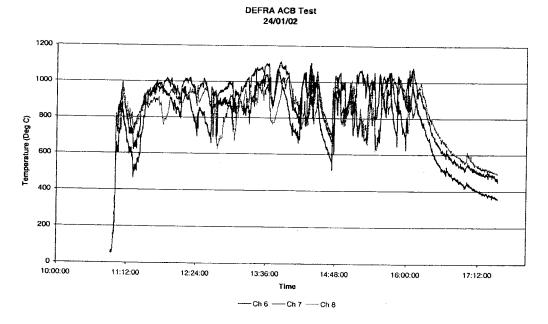
12:24:00

DEFRA ACB Test 23/01/02 Wood loading & Temperature

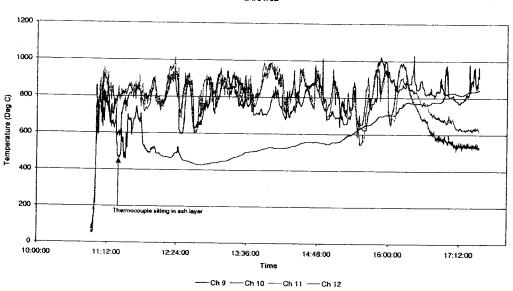


Appendix B. Results from the burns on Thursday 24th January 2002

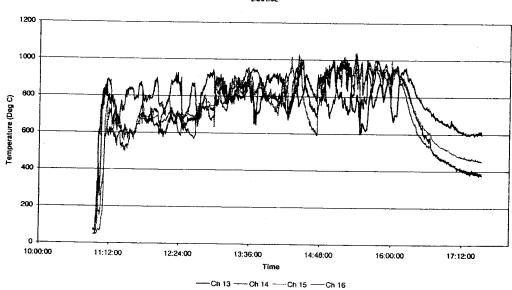




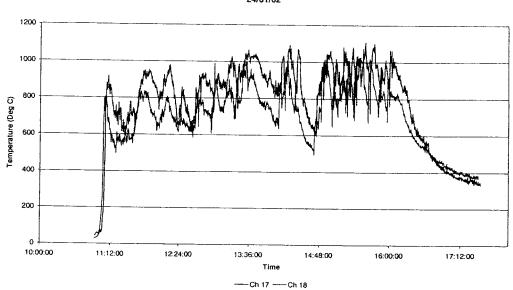




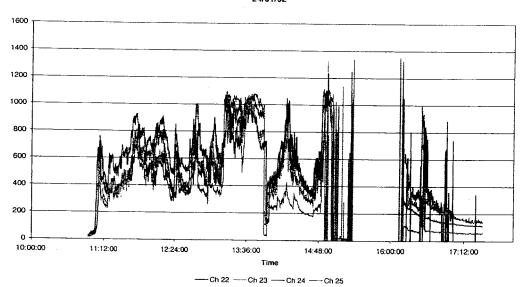
DEFRA ACB Test 24/01/02

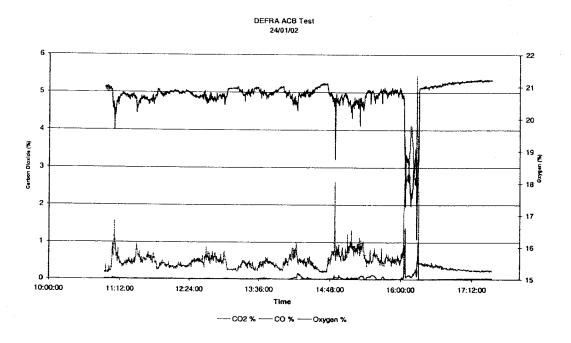


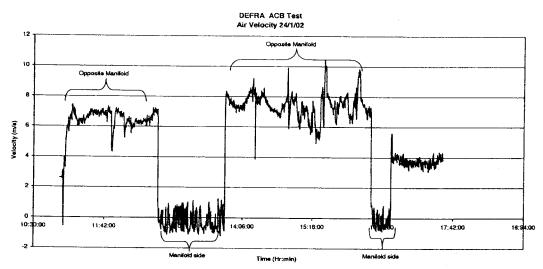




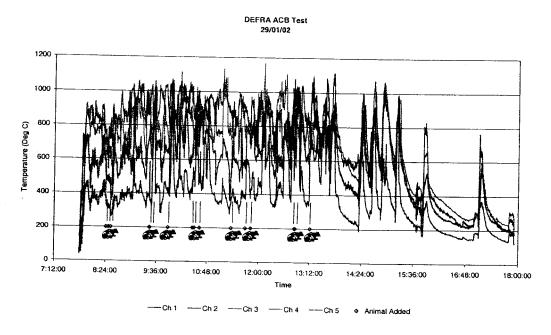
DEFRA ACB Test 24/01/02

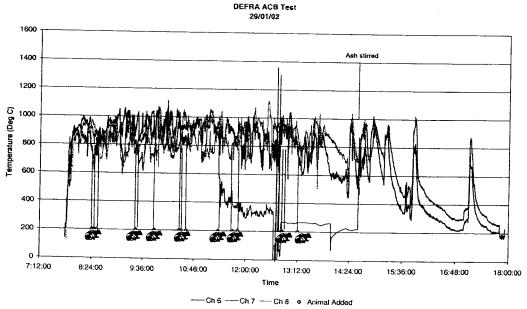


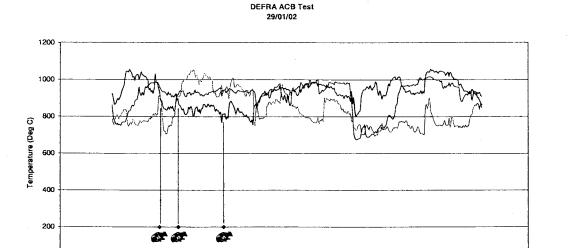




Appendix C. Results from the burns on Tuesday January 29th 2002







10:46:00

10:55:12

11:02:24

11:16:48

11:09:36

11:24:00

Channels 6 - 8 Expanded plot.

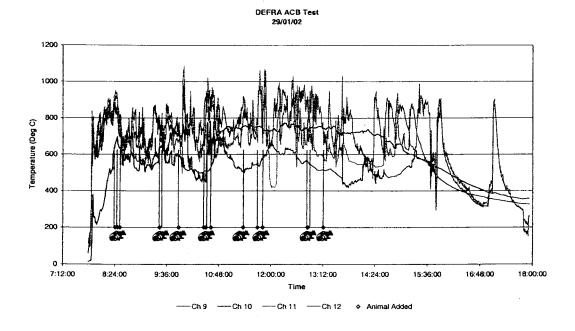
10:19:12

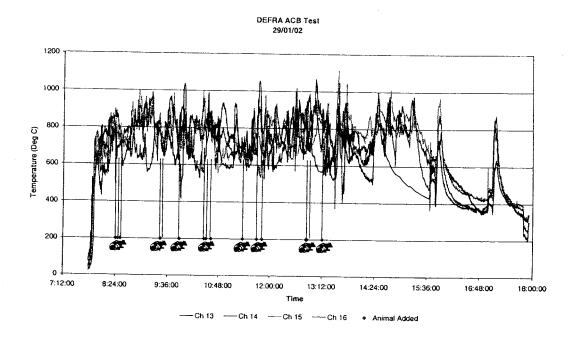
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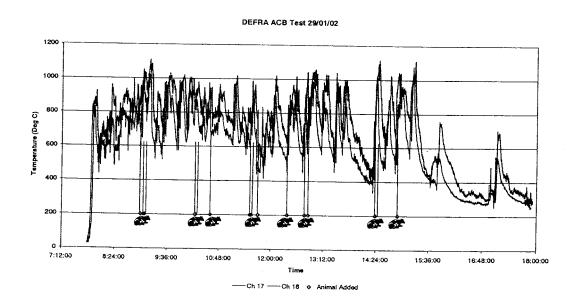
10:33:36

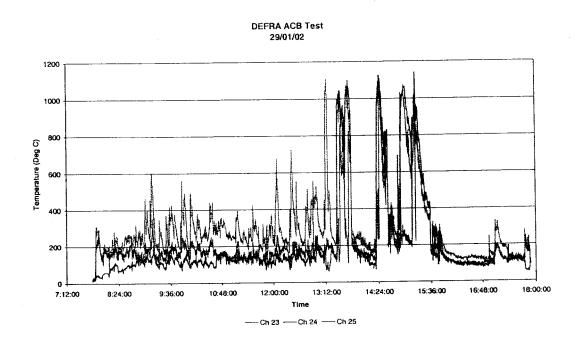
10:40:48

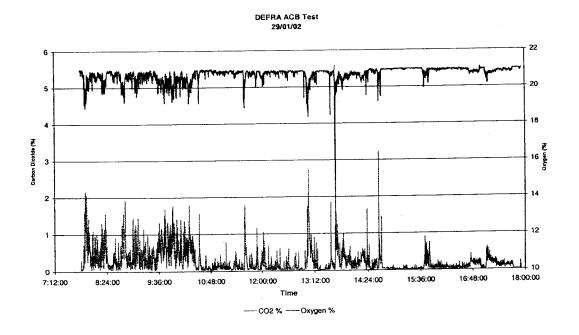
10:12:00











Gas analysis.

In the "above air curtain" position, the absolute concentrations of CO_2 were relatively low, averaging about 5000 ppm with brief excursions to 10,000 ppm and to below 500 ppm. CO concentrations were very low - mostly below 200 ppm. Oxygen concentrations generally ranged between 20.9% and 19.7%. Concentrations of these three gases at any point in time conformed extremely well to the expected oxygen balance. The low concentrations of CO_2 and CO and the small depression of CO_2 concentration from ambient (20.9%) was consistent with the relatively large dilutions with fresh air arising from the air curtain flow.

In the "below air curtain" position - i.e. in a combustion zone and with less dilution from the air curtain, the concentrations of CO and CO_2 could rise significantly with a corresponding drop in the measured O_2 concentration to preserve the oxygen balance.

Of more significance, in combustion efficiency terms, is the CO_2/CO ratio. The British Standards Organisation has published in BS 7899 Part 2, a table of "fire types" which are classified in terms of a small range of key parameters, including the CO_2/CO ratio as a measure of the combustion efficiency:

BS 7899 Part 2, Table 8: REVISED CLASSIFICATION OF FIRE TYPES						
Fire Stage or type		Temperature (°C)		Oxygen	Fire Effluents	
		Fire	Hot layer	to fire (%)	Oxygen from fire (%)	CO ² /
1.	Non-flaming			1		<u> </u>
a)	Self-sustaining	450- 600	RTª	21	>20	1-5
b)	Oxidative pyrolysis from externally applied radiation	300- 600	<50	21	>20	1-5
c)	Non-oxidative pyrolysis from externally applied radiation	300- 600	<50	0	0	<5
Whe size the t	ell Ventilated Flaming tree the fire size is small in relation to the of the compartment, the flames are below base of the hot layer and fire size is fuel rolled	>700	RT to 500	>15	5-21	>20 ^b
Whe the s partl	ess well Ventilated Flaming re the fire size may be large in relation to size of the compartment, the flames are y above the base of the hot layer and fire is ventilation controlled:					
a) S	Small vitiated fires in closed compartments	>700	RT to 500	<15	0-12	2-20
	Post-flashover fires in large or open opportments	>700	500 to1000	<15	0-12	2-20

RT = room temperature.

^bMay be lower if the burning materials contain fire retardants. In order to determine whether flaming decomposition conditions in a particular apparatus fall into category 2 or category 3 it is