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BURNTHROUGH RESISTANCE OF FUSELAGES: INITIAL FINDINGS

An investigation into the burnthrough resistance of fuselages and the effects of soot deposition in the early stages of a pool fire on burnthrough time

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Summary

A rapid burnthrough of a structurally intact fuselage occurred in the B737 accident at Manchester in 1985. This initiated a study into improvements of burnthrough resistance or fire hardening of aircraft fuselages to delay the ingress of the fire and associated toxic gases so increasing the survivability time within the cabin. On behalf of the Civil Aviation Authority, Faverdale Technology Centre (FTC) is currently developing a fire test facility and procedure to enable an investigation into methods of fire hardening the fuselage in existing and future aircraft designs to take place. Experience from both accidents and full scale tests have shown that for a typical aircraft, there may be potential for the fuselage to be fire hardened to delay the penetration of an external fire into the passenger compartment.

The investigation into improving the fire hardening of aircraft fuselages is part of the CAA's ongoing programme to improve aircraft passenger safety with regards to fire.

The initial phase of the project involved the definition of a heat source that was representative of a post crash pool fire. This definition was based upon previous test work, accident data and theoretical calculations. The conditions representative of an engulfing pool fire were concluded to be a temperature of 1150°C and a heat flux of 160 kW/m^2. Based on FTC's previous testing experience it was decided that the best method of producing such a repeatable heat source was by designing and building a dedicated gas fired test facility.

The next phase of work covered the design and building of the facility. A series of trials demonstrated that the facility produced a heat source that simulated a pool fire without the inherent fluctuations in temperature and heat flux of a real fire.

During the commissioning some simple burnthrough trials were conducted on aluminium panels. When compared with the FAA's full scale test results, a marked difference was shown in burnthrough times. In comparable cases FTC's panels were burning through 2 or 3 times slower than the panels in the FAA's full scale tests.

After further trials it was concluded that this discrepancy in burnthrough times was due to soot being deposited on the sample in the early stages of the pool fire. The reason being that the deposition of soot on the surface of the sample leads to an increase in surface emissivity. This results in a greater amount of radiant energy being absorbed, leading to shorter burnthrough times.

At this stage it was decided that in order to understand more fully the effect of soot deposition on aluminium panels in the early stages of a pool fire and its relationship to burnthrough time, an additional investigation was required.

A simple sooting rig was constructed and a number of aluminium panels of different thicknesses were exposed to a small pool fire for different lengths of time. A clean aluminium panel has an emissivity of approximately 0.10. When exposed to the small pool fire the emissivity of the panel increased with exposure time to the flames. After an exposure time in excess of 30 seconds the emissivity of the aluminium panels tended towards a value between 0.50 and 0.80.

A series of burnthrough trials were conducted using the sooted aluminium panels. By using panels with different emissivities a relationship between emissivity and burnthrough time was obtained. The time for burnthrough to occur decreases as emissivity increases up to a

value of emissivity of 0.6. Once a value of surface emissivity of 0.6 has been reached any subsequent increase in emissivity has only a small effect on burnthrough time.

It was concluded that for the test facility to represent accurately a post crash pool fire the emissivity of the sample must be controlled. A technique has been developed for pre-conditioning samples with soot allowing the emissivity to be controlled. The technique enables soot to be deposited without the need for the sample to be exposed to intense fire conditions.

Faverdale Technology Centre and the CAA are liaising with the FAA's full scale test programme and aiming to use the facility as a screening device for materials and system improvements under consideration by the aircraft industry, before testing them in the full scale facility involving open pool fires burning through an aircraft fuselage.

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1 INTRODUCTION

1.1 Background

The investigation into fuselage burnthrough covered in this document is part of the CAA and FAA's on-going research programme into improving fire safety which has already resulted in several important regulatory changes over the last decade, as discussed in detail in a paper produced by R Hill (FAA) and N J Povey (CAA) (Ref 1).

Most of these have been aimed at controlling the spread of fire through the cabin and reducing the harmful effects of flashover. This has been achieved primarily through the introduction of low heat release standards for cabin materials and fire blocking layers for seat cushions.

Other recent changes that have been implemented help improve evacuation times by providing passengers with illuminated exit aisles in emergency situations and also by assuring that evacuation slides will not deflate when exposed to high levels of radiant heat which is typical during large ground fires.

An accident that highlights the significance of fuselage burnthrough resistance occurred in 1985 when a British Air Tours B737 was departing from Manchester International Airport in England. Just prior to take off, the Number 1 engine failed and ruptured the port wing fuel tank, igniting a large pool fire.

According to the Air Accident Investigation Branch (AAIB) report the extensive loss of life was attributed to a rapid fuselage burnthrough into the passenger cabin. Of the 131 passengers and 6 crew on board, 55 people lost their lives from rapid incapacitation due to inhalation of toxic emissions from the burning interior materials. One of the major contributory factors was the vulnerability of the aircraft hull to an external fire. The AAIB report (Ref 2) also speculates that the burnthrough occurred within 60 seconds of the aircraft coming to a stop. The catastrophic results of this accident are perplexing in that the fire was caused by an engine burner shell failure with no resulting loss of aircraft control or crash. The fuel involved in the fire was limited in amount, and the rescue and fire-fighting services responded rapidly.

The burnthrough resistance of fuselages is becoming increasingly more important when seen in the context of future aircraft design. A move to 700–800 seat ultra-high capacity aircraft (UHCA) is seriously being considered by aircraft manufacturers.

1.2 Aims & Objectives

This project forms part of a complementary programme of study agreed between the CAA and FAA. The programme addresses two major concerns of structural fire safety:

(1) The time taken for an external fuel fire to burnthrough the fuselage skin and insulation system and into the passenger cabin.

(2) The increasing use of composite materials in the primary and secondary aircraft structure.

The ultimate aim of the project is to develop a small scale facility and burnthrough test method to be used as a screening device for materials under consideration, thus enabling new systems of protection to be developed. The ultimate aim is therefore to use the facility to bring about improvements in the fire protection of fuselages.

Several phases of work have been programmed to achieve this aim:

(i) the definition of a representative heat source based upon accident and previous experimental data (Phase A);

(ii) the building and commissioning of the small scale test facility (Phase B);

(iii) the investigation of the importance of soot deposition on the fuselage and the resulting change in surface emissivity with respect to increased burnthrough times. (Phase B1);

(iv) the conducting of burnthrough tests on mock-up fuselage panels (Phase C);

(v) the conducting of burnthrough tests on existing and protected fuselage specimens. (Phase D).

2 STUDY INTO DEFINITION OF HEAT SOURCE (PHASE A)

2.1 Introduction

The purpose of the initial phase of the fuselage fire hardening investigation was to define a heat source, representative of a pool fire. This definition was to be based on previous test work, accident data and theoretical calculations.

The definition was then to be used as the basis for specifying the factors needed in designing a small scale repeatable test facility to study the fire hardening of aircraft fuselages.

2.2 The Study

The search for information to define the heat source was concentrated on previous published test work. This work was itself based upon previous studies of post crash fires and the study of general pool fires.

The resultant experimental data produced a wide range of results for the temperatures and heat fluxes developed by hydrocarbon pool fires. Therefore the selection of a representative fire was difficult, as expected though, from previous FTC work, the data tended towards an upper value. This was then taken into consideration when proposing the upper values of temperature and heat flux to represent the heat source. The values taken were the mean of the highest temperatures and heat fluxes taken from the previous experimental data.

The values are given below:

Temperature = 1150°C

Heat flux = 160 kW/m^2

Gas velocity = 2 m/s at 1150°C

Fire status = Fully developed

Profile of fire curve = Instantaneous rise to maximum level.

The values given above agree with values that FTC have previously experienced in fire scenarios relating to both the aircraft industry and industry in general.

The definition of the maximum gas velocity was based upon a limited amount of information and for the purposes of this investigation was taken to be 2 m/s (see Appendix IX).

As well as upper values of temperature and heat flux for the heat source, lower levels of heating were also considered. These levels were intended to represent a pool fire at a distance from the fuselage. However, in the previous results covered there was no reference to a lower level of heating. So in the absence of data it was decided that the maximum duration of heating required would be 10 to 15 minutes. At the end of which the aluminium skin should have just melted. The lower level was therefore taken as the temperature at which the aluminium skin would typically melt.

Temperature = 650°C

Heat flux = 42 kW/m^2

FTC and the CAA had agreed to cross relate wherever possible with the FAA's full scale fuselage fire hardening investigation. It was expected that the FAA's test results would fall within the upper and lower levels as previously defined.

2.3 Conclusions

After discussions between the CAA and FTC and based upon FTC's previous testing experience it was decided that the best method of producing a standard repeatable heat source was by designing and building a dedicated gas fired unit. Included in Appendix II is a theoretical discussion of the factors considered in simulating an external heat source.

The unit was to consist of a mild steel box lined with ceramic fibre and was to be powered by four propane burners. The test sample was to be supported above a sliding lid in the roof section of the furnace. A diagram of the facility is shown in Appendix V.

The proposed method of operation was to heat the furnace up to a known temperature and then by rolling back the insulated door, subject the test piece to the desired conditions of temperature and heat flux. This method of storing energy and then releasing it provides in a repeatable manner the required conditions in the form of an instantaneous rise.

Whilst defining the heat source an opportunity arose to conduct an indicative test on a commercial aluminium panel. This panel started to burn through after 80 seconds with a furnace aperture temperature of 950°C.

This simple indicative test demonstrated that the basic principle of using a furnace to simulate a pool fire scenario was a sound one.

3 THE COMMISSIONING OF THE TEST FACILITY (PHASE B)

3.1 Introduction

The objective of the next phase of the investigation was to characterise the heat source. This was to enable reproducible test results to be obtained from the representative fuselage specimens to be fired in the furnace. The initial phase had defined a heat source representative of a post crash pool fire which was used as the basis to design the small scale test facility.

The specification required a heat source that would simulate the maximum average conditions in a large aircraft fuel spillage fire. Those conditions being a heat flux of 160 kW/m^2 and a temperature of 1150°C. This test condition also had to be provided instantaneously and be maintained for a minimum duration of 5 minutes. This was achieved by heating the facility up to temperature then maintaining the temperature for 20 minutes before pulling back the rolling lid to reveal the heat source.

3.2 Characterisation Trials

One of the major aims of building the facility was to produce a heat source that simulated a pool fire without the inherent fluctuations in temperature and heat flux of a pool fire. A number of trials were devised to determine if:

(i) the facility could be operated between the desired upper and lower test limits.

(ii) reproducible results could be obtained across the full range of values.

A number of results from the tests are given in Appendix VI. The results demonstrated that the facility produced a controlled and repeatable test over a range of conditions.

When the values from the tests were compared to those measured in pool fires analysed in Phase A, the test facility demonstrated a significantly better level of reproducibility. The furnace temperatures were being held to within 2% of the desired value at 1150°C. This compared favourably with observed pool fire temperature fluctuations of up to 40%. The associated heat fluxes were reproduced with a level of repeatability of ± 12% at the higher temperatures. This compared to fluctuations measured in pool fires of up to 100%.

3.3 Burnthrough Trials

During the commissioning phase of the programme an opportunity arose to conduct some simple burnthrough trials to compare burnthrough times of the test facility with the FAA's full scale results.

When burnthrough tests were conducted and compared to the full scale test results that the FAA had conducted prior to embarking upon their full scale programme, a marked difference was shown in burnthrough times. In comparable cases the panels in our burnthrough trials were burning through 2 or 3 times slower than the panels in the FAA's full scale tests. See Figure 3.1. After re-checking and confirming the performance of the burnthrough facility, the values of temperature and heat flux being measured were in excess of those measured in the FAA pool fire.

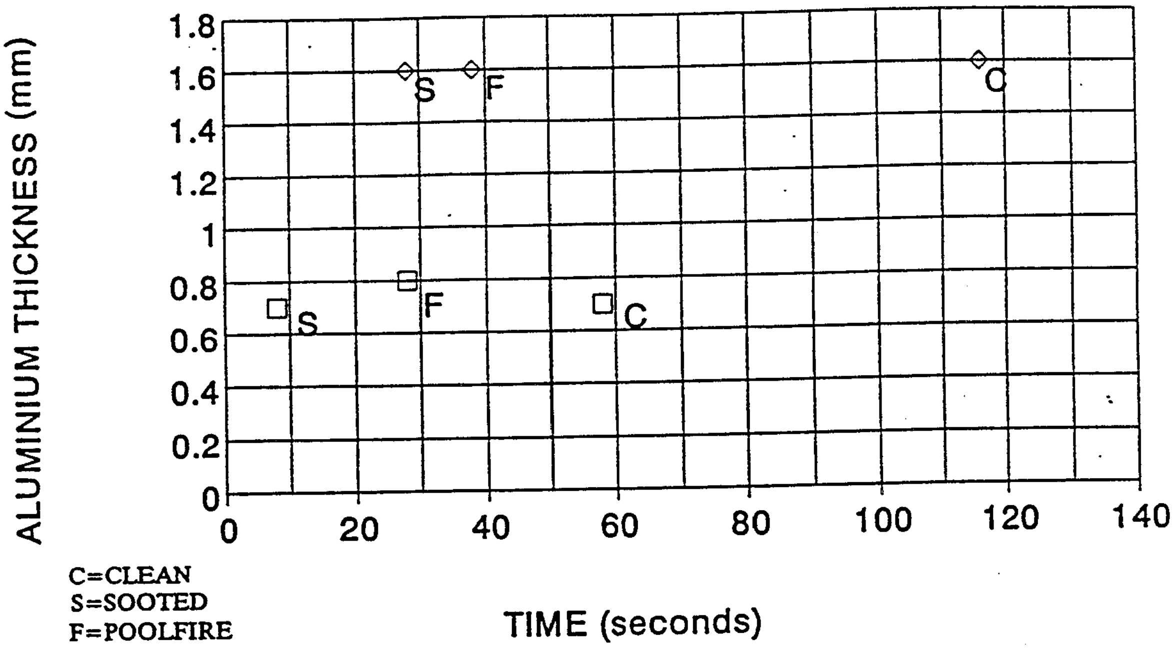


Figure 3.1 Aluminium thickness against burnthrough time

It was at this stage that the idea was first put forward that this apparent discrepancy in burnthrough times could be due to soot being deposited on the sample in the early stages of the fire.

More burnthrough trials were conducted on a small number of aluminium samples. The aluminium tested was grade 6061 and 1.6 mm thick. When tested under controlled conditions the samples burnthrough time was of the order of 180 seconds. As before, these results were not as expected. The FAA's full scale samples had burnthrough in 26 seconds for similar values of temperature and heat flux. However, after re-checking the test facility's instrumentation and test output data, it was shown that the test facility was operating to the design criteria. The samples were receiving a constant heat flux and temperature in excess of the values measured during the FAA pool fire trials.

3.4 Discussion

At this stage more thought was given to the idea that, the factor that was causing shorter burnthrough times than expected was the amount of soot being deposited upon the panel surface. The reason behind this was that an increase in soot deposition had led to an increase in surface emissivity. Hence a greater amount of radiant energy had been absorbed. This resulted in a shorter burnthrough time.

In a typical industrial pool fire, the time to reach a high surface emissivity is relatively small when compared to the expected duration of the test. However, burnthrough times for aircraft fuselages are measured in only tens of seconds. Hence the time for the surface to reach a high emissivity could be critical.

Having established theoretically that soot deposition could be a major influence on fuselage burnthrough time, more trials were carried out. Tests were conducted on 0.7 mm aluminium panels. The same as those used during the commissioning phase. A panel in its as supplied condition burnt through in 58 seconds when it was positioned at a height of 50 mm above the aperture and subjected to a temperature of 1150°C and a heat flux of 200 kW/m^2. A similar panel was coated with a thin layer of soot from an acetylene flame and then tested in the same way. Burnthrough occurred in 8 seconds.

In order to try and identify the soot deposition process in more detail a crude sooting rig was constructed. A number of samples were exposed to a small scale pool fire for different time durations and their emissivities measured. As the exposure time to the pool fire increased the surface emissivity of the samples increased. At an exposure time of 30 seconds the surface emissivity of the sample had increased from 0.10, the emissivity of a plain aluminium sheet, to 0.45.

3.5 Conclusion

At this stage the facility had been commissioned and characterised. However, before progressing onto phase C of the fuselage burnthrough investigation it was decided to hold the main programme in order to investigate more fully the effect of soot deposition on aluminium panels in the early stages of a pool fire and its relationship to burnthrough time. As failure to understand this mechanism could have affected the understanding of the test results in later phases.

4 INVESTIGATION INTO THE EFFECT OF SOOT DEPOSITION ON BURNTHROUGH TIME (PHASE B1)

4.1 Introduction

As a result of the conclusion from phase B of the fuselage burnthrough investigation it was decided that before proceeding onto the next phase an investigation was to be carried out into soot deposition in the early stages of a pool fire and its effect on burnthrough time.

4.2 Description of Equipment

A test rig was constructed to carry out the soot deposition investigation and is shown in Appendix VII. The shell of the rig consisted of an rolled steel angle frame clad with mild steel open at the top with viewing windows situated around the side. This structure provided a suitable shielded environment to conduct the sooting trials within. The fire source was provided by burning a measure of kerosene floating on water in a steel tray. The tray incorporated a lid which could be lowered to extinguish the fire at a pre-planned time.

4.3 Test Method

The investigation consisted of a number of trials which provided information from which the rate of soot deposition and the increase in surface emissivity could be determined during the early stages of a pool fire.

The surface emissivity of the samples was measured by using a thermal imaging camera and referencing the image to a previously defined surface emissivity

The thickness of the soot covering on the sample was measured by using a mass balance technique on a small sample taken from the main test piece.

The tests were carried out as follows:

The sample was mounted into the test frame and a measure of kerosene added to the tray. The enclosure was then sealed. The pool of kerosene was then ignited and the test was deemed to have started when the pool fire was seen to be fully developed. On completion of the test the sample was removed from direct exposure to the fire and the fire was extinguished. Each test was recorded on a video camera. A thermal imaging scan was conducted on each test sample to produce a value for surface emissivity. A small sample was removed from a number of test pieces so that the thickness of the soot covering could be established.

4.4 Initial Soot Investigation

4.4.1 *Sooting Profile*

Aluminium panels 1.6 mm thick grade 6061 were used in the investigation. Initially a number of panels were exposed to a fully developed fire for the following durations 15, 30, 45, 60 and 75 seconds. The tests were duplicated to allow for burnthrough trials if necessary. Results from these tests are given in Appendix VIII. A plot of surface emissivity against exposure time to the fire is shown in figure 4.1. A wide variation of results occurred between 15 and 60 seconds. As the anticipated burnthrough time was in the region of 30 seconds

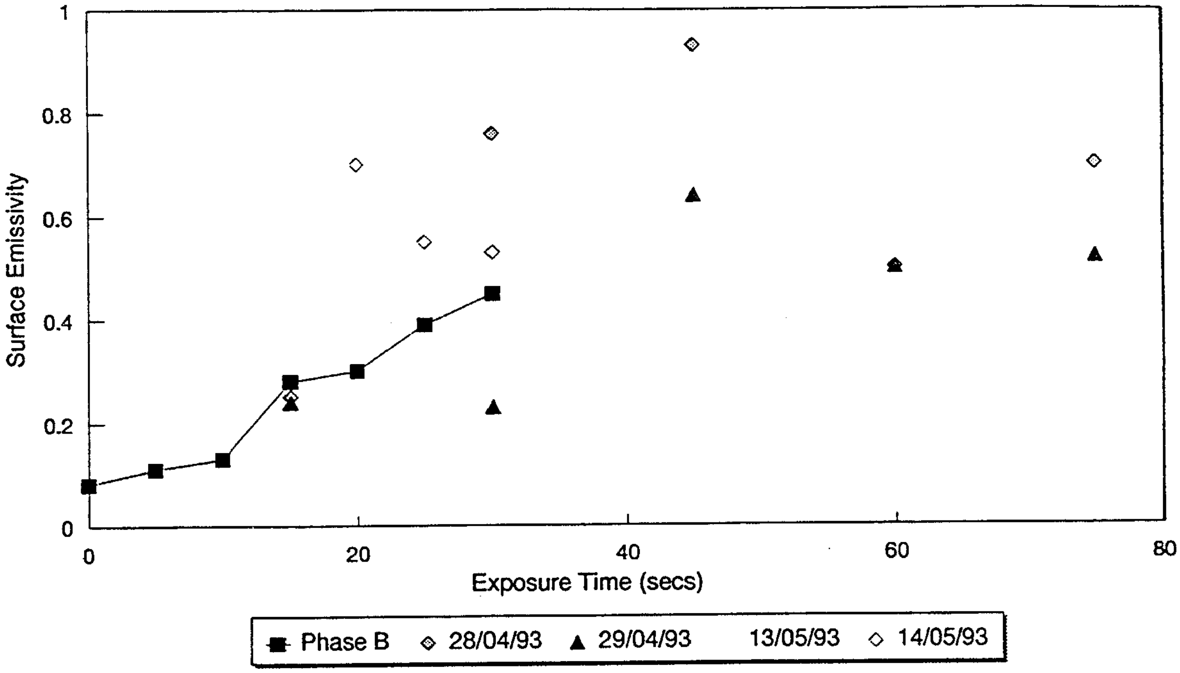


Figure 4.1 Surface Emissivity Against Time

to 60 seconds and as the greatest variation in results started occurring after 15 seconds it was decided more trials should be conducted for the following durations 20, 25 and 30 seconds. Results from these tests are given in Appendix VIII. These results are also plotted in Figure 4.1.

A plot of average soot thickness against time is shown in figure 4.2. From figure 4.1 it can be seen that the surface emissivity of the panels appears to increase approximately linearly with exposure time to the fire up to 35 seconds. After this point however, there appears to be a wide scatter of results. This is no doubt in part due to the fact that although the trials were conducted in a shielded facility the enclosure is an external one.

4.4.2 *Initial Burnthrough Trials*

From the sooting trials four panels were selected for burnthrough tests. The panels were chosen on the basis of their surface emissivities. Aluminium panels were tested with surface emissivities of 0.25, 0.50, 0.70 and 0.93. The results from these trials are shown in figure 4.3. From figure 4.3 it can be seen that some form of exponential relationship appears to exist between surface emissivity and burnthrough time.

4.4.3 *Initial Conclusions*

One of the main objectives of this initial investigation into soot deposition in the early stages of a pool fire was to formulate a proposal for the pre-conditioning of the samples for effective use in the burnthrough facility. From this initial testwork it seemed that an appropriate value for surface emissivity to more closely represent a real pool fire situation, was of the order of 0.6–0.8. The value of surface emissivity obtained from this initial testwork was only based upon the sooting of one thickness of aluminium. It was therefore decided that in order to identify and define the soot burnthrough relationship in more detail and to gain a more thorough understanding of the sooting phenomenon another investigation was to be carried out.

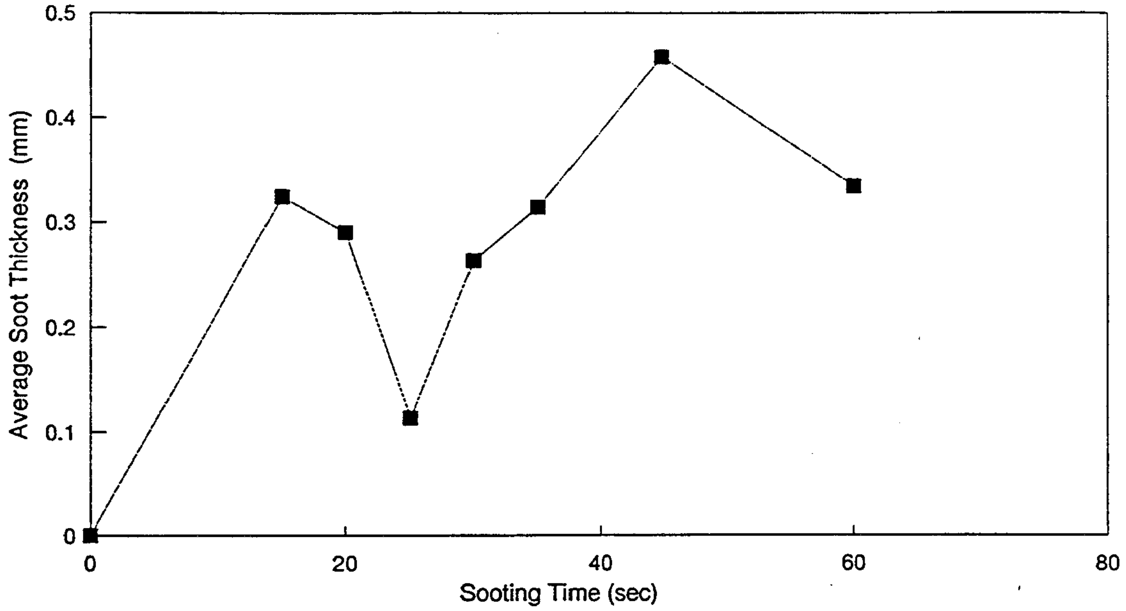


Figure 4.2 Average Soot Thickness Against Time

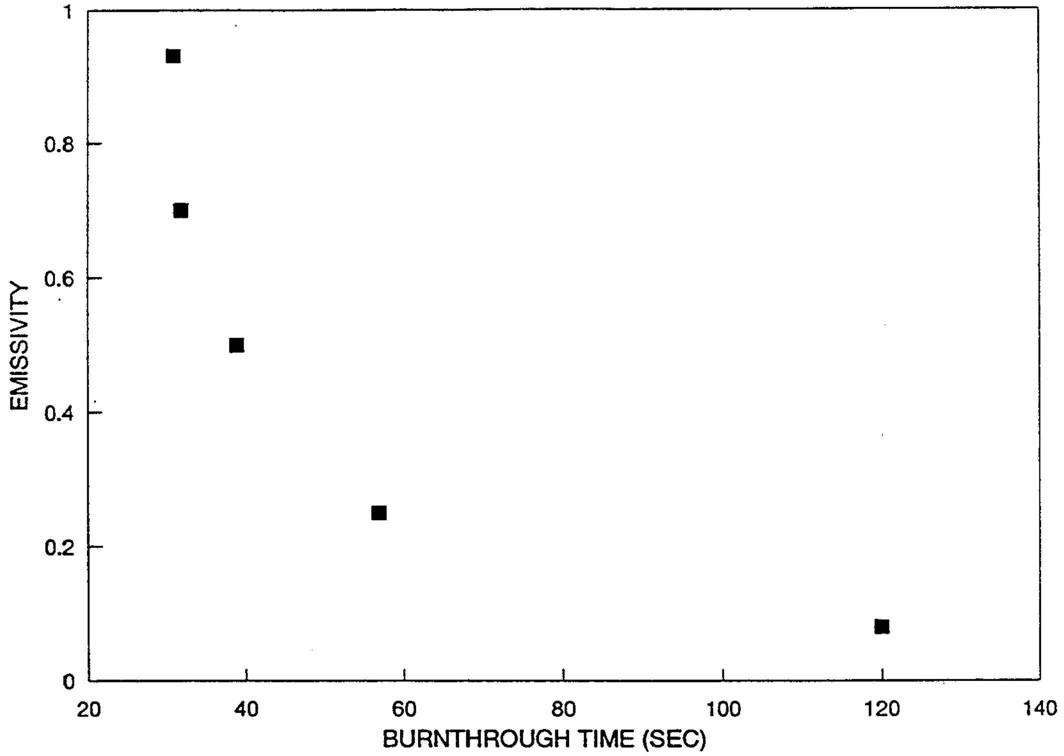


Figure 4.3 Emissivity Against Burnthrough Time

4.5 Additional Soot Investigation

4.5.1 *Introduction*

The next phase of the soot deposition investigation was a continuation of the work as previously described. The investigation considered the following typical materials which are currently in service

(a) 1.6 mm painted aluminium

(b) 0.9 mm aluminium

(c) 2.0 mm aluminium

(d) Composite material (floor panel)

Based on the results of the sooting trials samples of each material were to be selected for burnthrough trials, the object of which was to obtain as much information as possible and produce a burnthrough emissivity characteristic for each material.

4.5.2 Sooting Procedure

The sooting trials were conducted on the test rig as shown in Appendix VII, using the method as previously described. For each material 6 sooting tests were to be conducted. The durations of the tests for each material were to have been 10, 20, 30, 40, 50 and 60 seconds. The test durations being exposure time to a fully developed fire. Tests were conducted on the following thicknesses of aluminium, 0.9 mm, 1.6 mm and 2.0 mm. The 1.6 mm aluminium panels were pre-treated and coated with a polyurethane finish in white in an attempt to replicate the painted finish on aircraft panels.

The composite material panel was a structural grade laminate consisting of nomex aramid fibre/phenolic resin core faced on both sides with uni-directional cross-plied glass fibre skins.

4.5.3 *Sooting Profile Results and Discussion*

The results of the sooting trials are shown in Appendix VIII. A plot of surface emissivity against exposure time for the tests is shown in figure 4.4. From figure 4.4 it can be seen that the sooting profile for the 0.9 mm aluminium and 2.0 mm aluminium are almost identical. Both tend to a value of between 0.5 and 0.75 for surface emissivity, after an exposure time of 20 seconds. Smoke plumes and therefore the rate of soot deposition are highly variable phenomena, depending on wind conditions and orientation and size of fire. Thus as the trials were conducted in an external facility the test method inherently should have a degree of uncertainty. However, the most recent sooting trials appear to demonstrate a high level of repeatability.

The sooting profile for the 1.6 mm painted aluminium as seen in figure 4.4 appears to bear no relation to the profiles obtained from the 0.9 mm and 2.0 mm

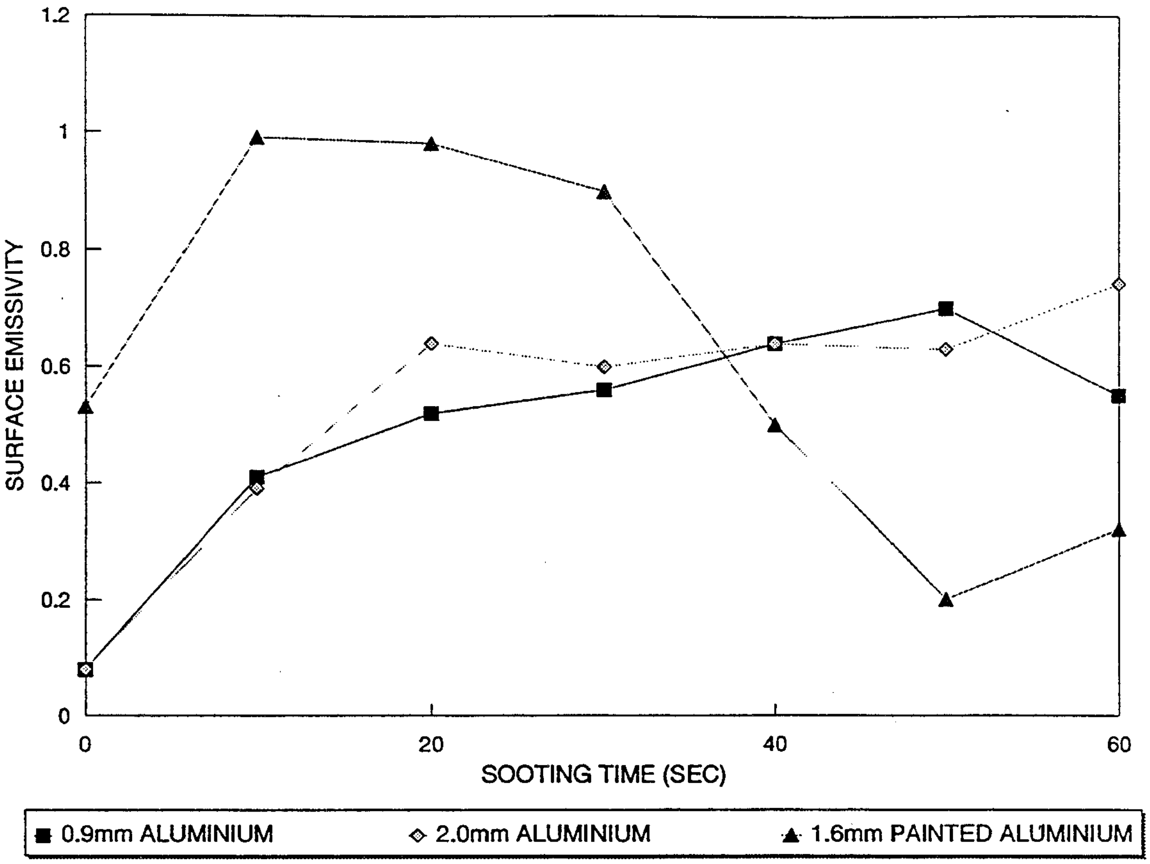


Figure 4.4 Emissivity Against Sooting Time

plain aluminium. However, an examination of the 1.6 mm panels after the sooting trials led to an explanation.

The clean painted aluminium surface had a surface emissivity of 0.53 as the exposure time to the pool fire increased. The addition of soot to the surface increased. This resulted in an increase in surface emissivity. However, after a certain exposure time the painted finish flaked off, leaving exposed aluminium. This resulted in a decrease in surface emissivity. As more paint flaked off, more aluminium was exposed. This in time accumulated soot as before, resulting in an increase in surface emissivity.

The surface emissivity of the composite material panel, before any sooting attempt was made, was measured to be 1.00. An attempt was made to soot one panel. It was placed in the test facility and exposed to the pool fire for a duration of 30 seconds. During the test the composite material gave off dense black smoke and charred rapidly. At the end of the test the panel was extensively damaged.

It should be noted that the pool fire used in the sooting investigation was smaller than a pool fire that would result from a post crash fuel fire. This was to enable a range of emissivities to be obtained so that a relationship to burnthrough time could be established. So, although in this investigation the surface emissivity of the aluminium increases to a value approaching 0.75 after 30 seconds exposure, for a large scale pool fire this may occur after only a few seconds.

All the tests carried out in the sooting investigation demonstrate the critical importance of the emissivity of the absorbing surface. The separate sooting trials showed that surface emissivity is dependent on the time that a surface is exposed to an adjacent enveloping pool of fire. In order to more fully understand this process and enable prediction work to be carried out, an attempt was made, using a probability approach, to produce a function of emissivity with exposure time, details of which are given in Appendix IV.

4.5.4 *Burnthrough Results and Discussion*

After an analysis of the results obtained from the soot deposition profile, it was decided that in order to obtain as much relevant information as possible, burnthrough trials were to be conducted on the samples listed below.

Material	*Sooting Time (secs)*	*Surface Emissivity*
0.9mm Aluminium	10 40	0.41 0.64
1.6mm Painted Aluminium	0 30	0.53 0.90
2.0mm Aluminium	0 10 40	0.08 0.25 0.64
Composite Material	0	1.00

A plot of surface emissivity against burnthrough time for the samples chosen is shown in figure 4.5 and the actual burnthrough times are given in Appendix VIII.

As can be seen from figure 4.5 the burnthrough times for each thickness of material appear to follow an exponential curve. The position and gradient of the curves on the burnthrough axis depending on the thickness of the aluminium panel.

From figure 4.5 it is also apparent that once the original emissivity is of the order of 0.6–0.7 any increase in original emissivity subsequently produces a very small decrease in burnthrough time. So that for original emissivities of between 0.6 and 0.9 burnthrough times would be very similar.

As a result of all the test work carried out to determine burnthrough times, an attempt was made to develop a heat transfer model for the burnthrough process to enable prediction of burnthrough times to be made. A discussion of the parameters involved in developing such a model and details of the model are given in Appendix III.

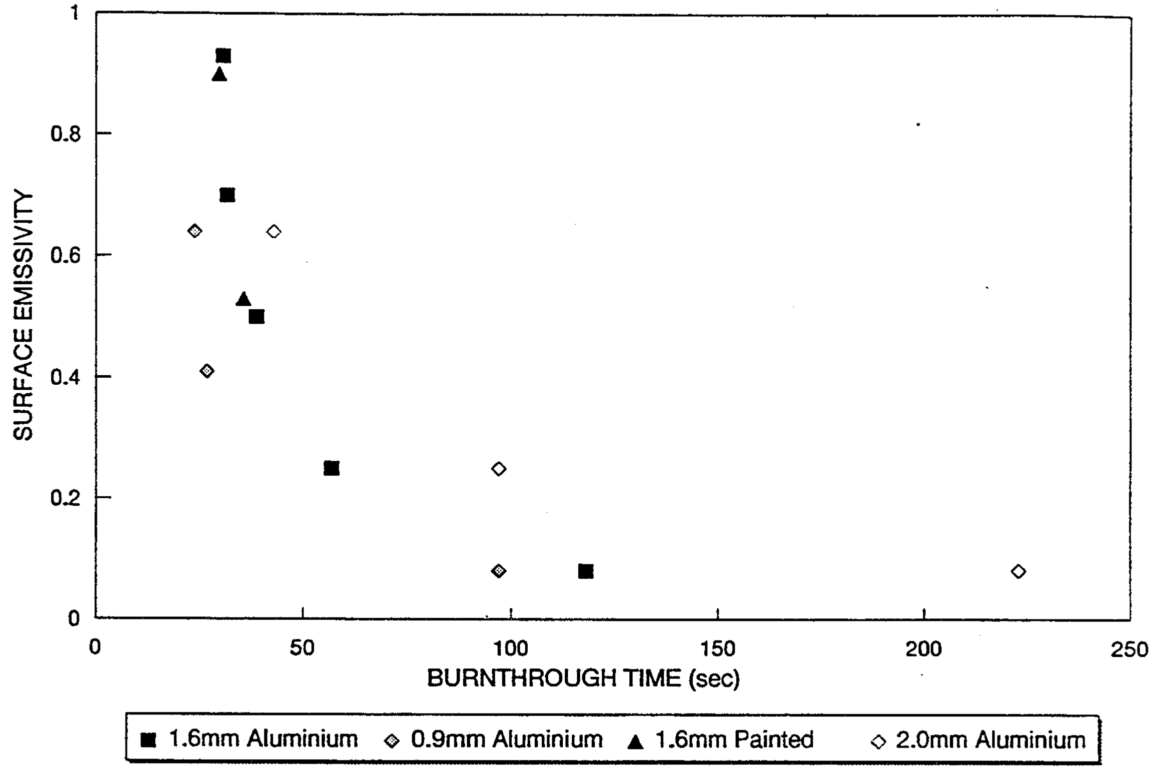


Figure 4.5 Emissivity Against Burnthrough Time

5 COLD SOOTING TECHNIQUE

5.1 Introduction

The work conducted in the main body of this document concluded that in order for the small scale test facility to represent accurately a post crash fuel fire it is desirable for the samples to be tested to have a surface emissivity value that lies between 0.6 and 0.9.

Therefore, before testing in the burnthrough facility, all samples need to be pre-conditioned to an appropriate emissivity value. So that a wide range of materials can be tested it was necessary to develop a method for sooting samples without the risk of heat damage occurring.

5.2 Description of Equipment

A sketch of the cold sooting rig is shown in Figure 5.1. The rig comprises a modular racking system. A frame, into which the sample is placed, is laid across it. The sample frame has a runner at each corner which enables the frame to traverse smoothly along the racking system. The rig is placed in a sealed enclosure.

A wire and pulley arrangement allows the frame containing the sample to be moved along the rig. The movement of the sample is controlled from outside the enclosure.

A tray is positioned centrally underneath the rig. The tray, as shown in Figure 5.2, contains a strip of ceramic fibre material soaked in kerosene. A cover is positioned over the tray so that only a narrow strip of material protrudes.

5.3 Method

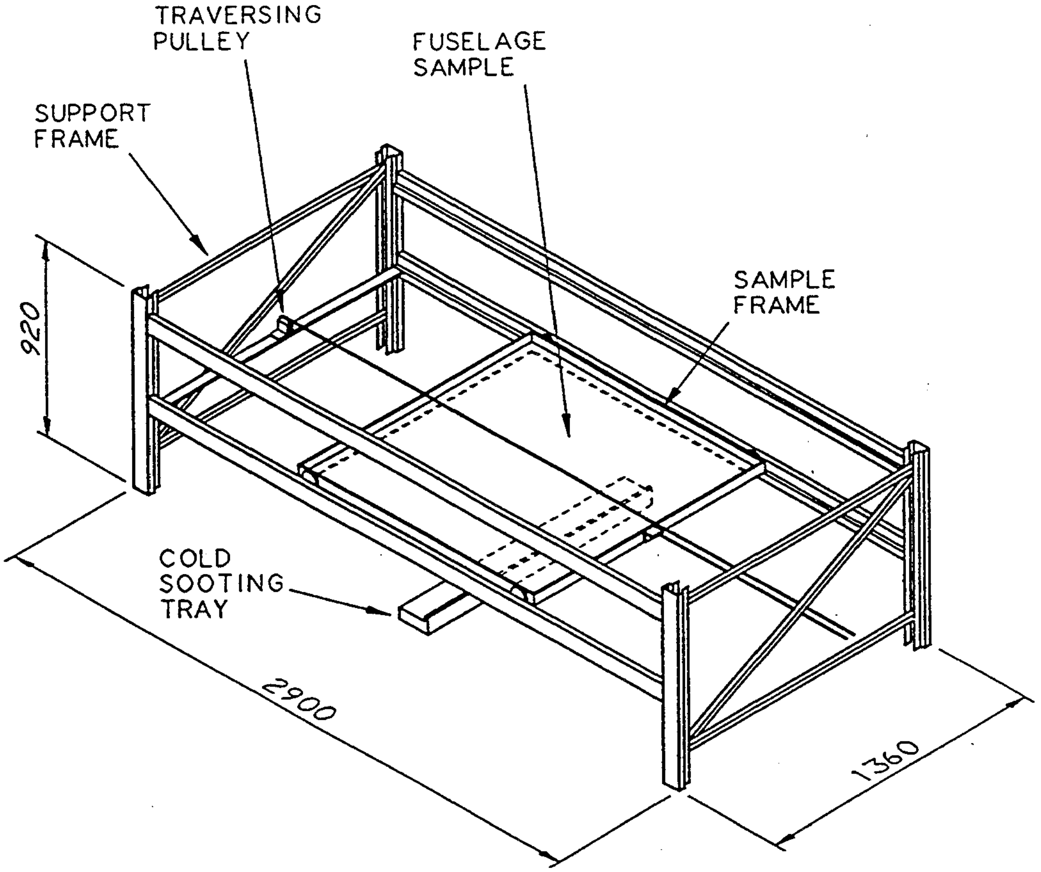
The sample to be sooted is placed in the sample frame, which is positioned approximately 350mm above the cold sooting tray. The strip of material soaked in kerosene is then ignited. The narrow strip of ceramic fibre acts as a wick and produces a controlled even flame, with a high soot content, along its length. The sample is traversed back and forth along the rig at a constant rate (approximately 10m/min) for 15 minutes. After 15 minutes the flame is extinguished. The sample is then removed from the frame when the enclosure can be entered safely.

5.4 Results and Discussion

The movement of the sample continually across the flame prevents any significant temperature rise on the surface of the sample. This eliminates any potential heat damage being caused to the sample.Hence the term cold sooting.

A number of tests were conducted on aluminium panels. When the surface emissivities of the sooted side of the aluminium panels were measured using a thermal imaging camera, they were found to be consistently between values of 0.6 and 0.90.

With the development of this cold sooting technique, materials can now be pre-conditioned to an appropriate emissivity representative of a large scale pool fire, before testing in the small scale facility.



FAVERDALE TECHNOLOGY CENTRE

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England

title

ISOMETRIC VIEW OF COLD SOOTING RIG

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checked	M.A.S.	14.12.93	N.T.S.	design sketch no DSK/21-0252/21
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Figure 5.1

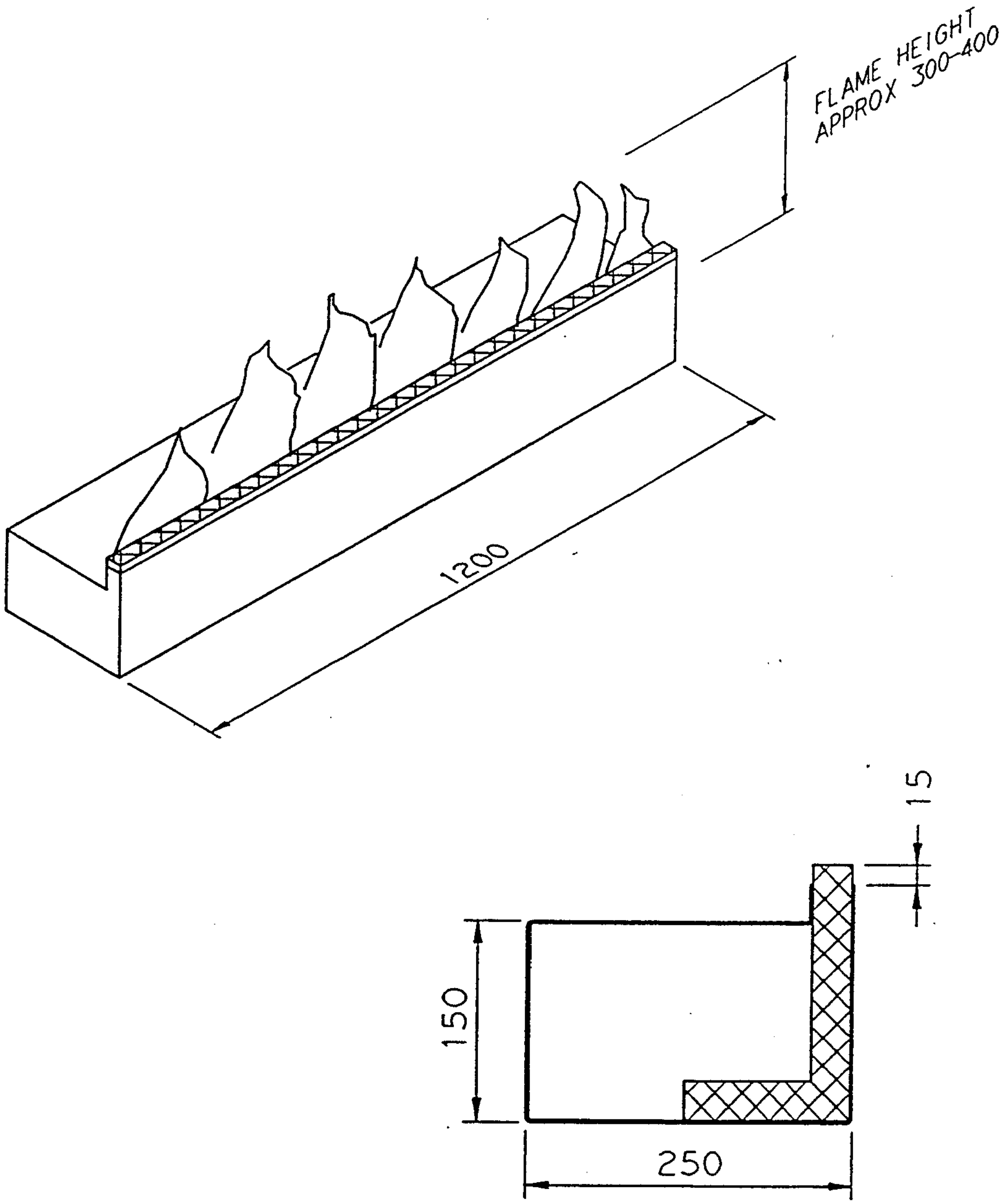

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Figure 5.2

6 CONCLUSIONS

(a) We have concluded from previous analytical work that typical conditions representative of a post crash engulfing pool fire are a temperature of 1150°C and a heat flux of 160 kW/m^2.

(b) A small scale facility has been constructed which is capable of reproducing the conditions that exist in a large scale pool fire without the inherent fluctuations of a real pool fire.

(c) The condition of a fuselage surface is a critical factor in the determination of burnthrough times. Burnthrough time decreases as surface emissivity increases.

(d) In the early stages of a pool fire soot deposition on the fuselage surface leads to an increase in surface emissivity.

(e) In the early stages of a pool fire the emissivity of the fuselage surface tends to a value of 0.6–0.9.

(f) Once surface emissivities of the order 0.6–0.7 have been reached any increase in emissivity subsequently produces a very small decrease in burnthrough time. So that for original emissivities of between 0.6 and 0.9 burnthrough times are very similar.

(g) Using a cold sooting technique, samples can be pre-conditioned to simulate the expected conditions of the fuselage in a pool fire scenario.

(h) A small scale facility and burnthrough test method have been developed which are capable of being used as a screening device for materials under consideration, thus enabling new systems of protection to be developed. The facility can now hopefully be used to bring about improvements in the fire protection of fuselages.

7 REFERENCES

1 Richard Hill (FAA) Nick J Povey (CAA)

'*The Future of Aircraft Cabin Fire Safety*' a paper given at the International Conference for the promotion of advanced fire resistant aircraft interior materials, Atlantic City, New Jersey, USA, February 9–11 1993.

2 Air Accidents Investigation Branch (1988) '*Report on the Accident to Boeing 737-236 Series 1 G-BGJL at Manchester International Airport on 22 August 1985.*'
Aircraft Accident Report 8/88, London: Her Majesty's Stationary Office.

3 William H McAdams (1985) '*Heat Transmissions*'
Third Edition: McGraw-Hill.

Appendix I Nomenclature

A = Area (m^2)
V = Gas velocity (m/s)
T = Temperature (deg K)
F = Geometric View Factor (Dimensionless)
E = Surface emissivity (Dimensionless)
K = Thermal Conductivity W/mK
σ = Stefan Boltzmann. 5.67×10^{-8} W/m^2 K^4
D = Opening size of Faverdale Test Furnace (m)
h = Heat transfer coefficient (W/m^{2}K)
Nu = Nusselt number
= $h_c \cdot D/K$
Re = Reynolds number = $\dfrac{\rho \cdot D \cdot V}{\mu}$

k = Optical Extinction Coefficientx
x = Thickness of Flames (m)
R = Radius (m)
ρ = Density (Kg/m^3)
μ = Viscosity (Kg/ms)
L = Thickness (m)
C = Specific Heat (J/Kg K)
Q = Heat Flux.(W/m^2)
HF = Latent Heat of Fusion (J/Kg)
t = Time (seconds)
d = Duct Diameter (m)
G = Gas Volumetric Flow Rate (m^3/s)

Subscripts

f = Furnace
a = Ambient
s = Surface of aluminium sample
c = Convective
r = Radiative
e = Exit
i = Inlet
g = Gas

Appendix II Heating Mechanisms

1 In general where a surface is exposed to a fire, there will be interchanges of heat from a combination of sources.These sources can be summarised as:

(i) radiation from fire;

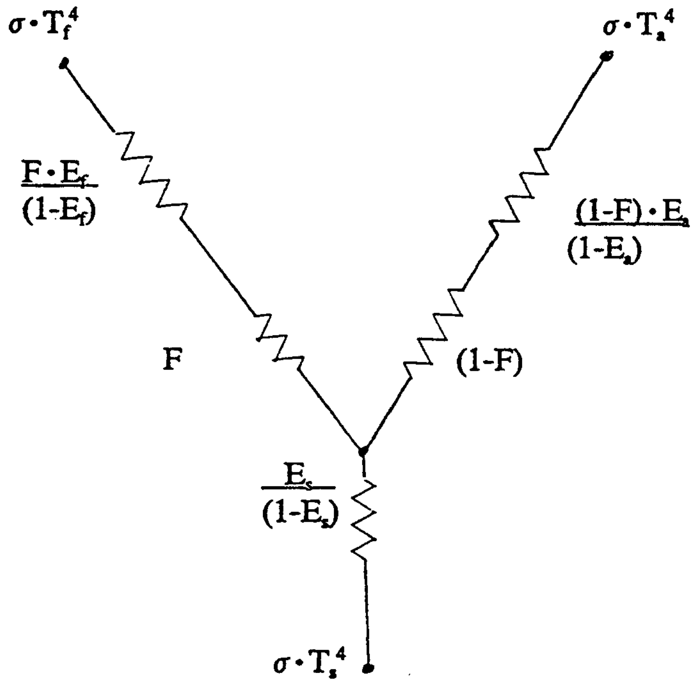
(ii) radiation from ambient surroundings;

(iii) convection.

In the situation where an aircraft fuselage is subjected to fire conditions, a transient situation arises where heat picked up by the exposed outer area of fuselage is partially absorbed by the fuselage skin and partially transmitted to a cooler ambient within the body of the fuselage.

1.1 Radiation

In situations where a post crash fire occurs, it is not necessarily the case that a fire would be directly adjacent to the fuselage, totally engulfing the local area. In general the fire source will be centred some distance away from the fuselage surface being considered. In this situation, the fuselage will 'see' areas of cool ambient surroundings in addition to the fire source. Analysis of radiant heat fluxes in these situations can conveniently be dealt with by referring to an equivalent conductance network. For the analysis considered here the relevant conductance network is as shown below:



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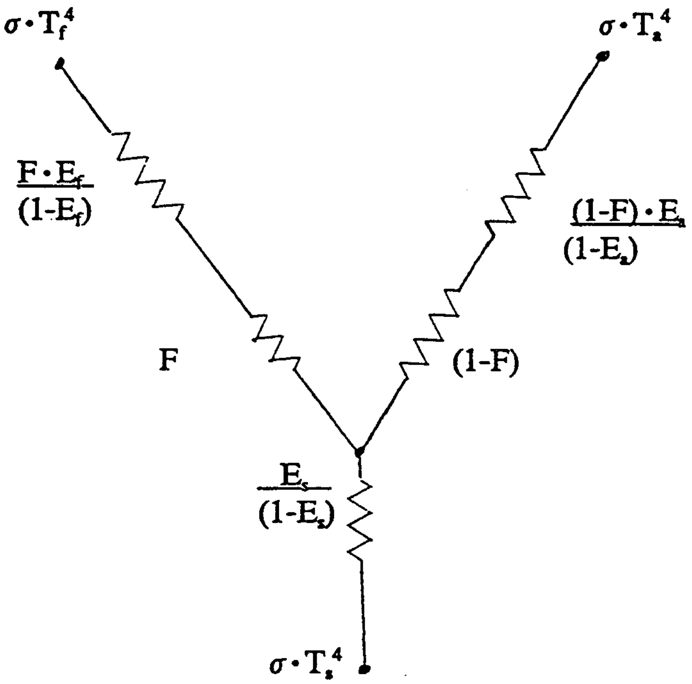


Radiation heat fluxes are calculated by solving heat flows (W/m^2) in the network, using emissivity values (σT^4) of the respective positions. This approach includes for both the successive reflections of radiant heat flux between surfaces and the furnace to fuselage surface geometric view factor (F). From the network it can be seen that where a fire totally engulfs the fuselage, and the geometric view factor (F) between the flames and the fuselage is unity. Then the radiative heat flux interchange with the ambient, being blocked out by the flames, becomes zero. Hence the view factor between ambient and fuselage (1-F) becomes zero.Similarly where a fire is small, or a large distance away, then F tends to zero. In this situation of the course, view factor to ambient tends to unity and the fuselage only sees ambient conditions.

It can also be seen from this network that radiant heat fluxes to the fuselage surface is critically dependent on its surface emissivity. By way of illustration taking a value of $F = 1$ (engulfing fire) radiant heat flux between furnace at T_f and fuselage T_s and solving the network gives

$$Q = \frac{E_f \cdot E_s}{E_f + E_s - E_f \cdot E_s} \quad \sigma \cdot (T_f^4 - T_s^4)$$

Tested values of surface emissivities vary from 0.08 for clean aluminium up to 0.95 for well sooted samples. For a furnace emissivity (E_f) at 0.9 the factor $\frac{E_f \cdot E_s}{E_f + E_s - E_f \cdot E_s}$ varies from 0.0684 up to 0.859. A factor of 12.6 to 1.

1.2 Convection

Convective heating in a large pool fire condition is due to gas movements over the cooler surface and is dependant on gas properties and gas velocities. Various sources and reports have estimated gas velocities within a pool fire, to be approximately 4 to 10 m/second with standard deviations of half the velocity. However, estimates also show that this is a relatively minor proportion of total heat flux, approximately 10–20%.

For the purpose of analysing results from the Faverdale test furnace a measured gas velocity at 2m/sec has been achieved. With this value being used in a modified version of equation 10.6. (Ref 3).

$$Nu = FACT \cdot 0.37 \cdot Re^{0.6}$$

where FACT is a factor of 5.85, derived from analysis of furnace results. This equation also gives the convective component of heat flux at approximately 18% of the total which agrees with estimates from other sources.

1.3 Heat Sources

Most tests on fire hardening investigations use a pool fire as the heat source. These suffer from very considerable lack of repeatability, but do have the same mechanism as real crash fires. To overcome the lack of repeatability FTC have adopted the use of a furnace with a known, controllable and accurately repeatable performance.

Factors affecting the heat picked up by a surface (fuselage) from a fire as discussed above are the source temperature, emissivity and the geometric view factor between source and surface.

1.3.1 *Pool Fire*

In a pool fire with sooty spectrally grey flames, an expression commonly used to calculate source emissivity is

$$E = 1 - \exp(-k \cdot x)$$

where k = Extinction coefficient ($\approx 1\ \mathrm{m}^{-1}$)
x = Thickness of flames (m)

Therefore for a large engulfing fire, approximately 3m or larger $E \rightarrow 1$.

Also, for a large engulfing pool fire, the geometric view factor (F) will be unity.

Temperatures associated with pool fires are perhaps their most variable feature, with temperatures fluctuating during the period of a single test by a factor of up to 2 in some cases. However, maximum temperatures reported have a ceiling of approximately 1150°C.

1.3.2 *Adjacent Fires*

The discussion so far has been based on an engulfing fire where the aircraft skin or other component is covered by optically thick flames and thus receiving the maximum heat flux.

However, this may not always be the case. There may be potential situations where the region concerned is not engulfed by flames, in which case it is necessary to consider the fire to be some distance away.

Where this is the case it is proposed that heat fluxes falling on a surface be calculated from the source fire of defined pool area and distance. Then the temperature and heat flux from the test furnace can be turned down to simulate the calculated values.

1.3.3 *Faverdale Test Furnace*

For the Faverdale test furnace, an emissivity value of 0.9 is used for its opening. The furnace has numerous internal reflecting surfaces which act so as to approach a black body. The resultant emissivity therefore lies between 0.8 for the internal components and 1.0 for the perfect black body. Temperature can be controlled within nominally 2% and up to 1150°C.

The view factor for a sample over the furnace opening can be varied within narrow limits and calculated with a short algorithm during computer simulation.

Appendix III Prediction of Burnthrough Times

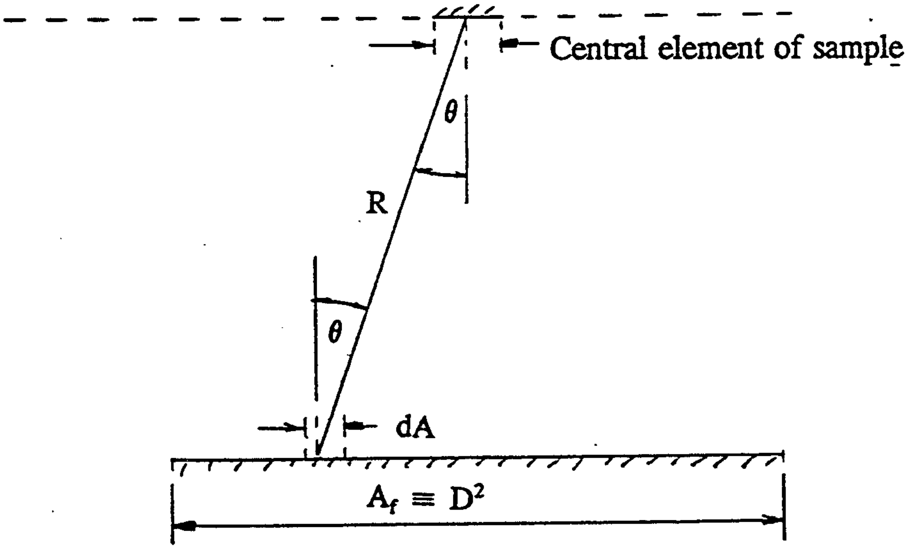
When an aluminium plate is heated from one side, for example by a fire or a furnace opening and permitted to cool from the opposite side to a cool ambient temperature then a simple heat flow balance gives:

$$\mathrm{Qin} - \mathrm{Qout} = L_s \cdot D_s \cdot C_s \cdot \frac{d}{dt} T_s \qquad (1)$$

Where Qin and Qout are the heat flows in and out respectively. With aluminium, melting takes place over a range of temperatures (ΔT) while at the same time absorbing latent heat of fusion (HF). Over this range of temperatures it is reasonable to consider the value of C_s as being modified on the basis that latent heat absorbed is divided evenly over the melting range. Therefore up to the start of melting, C_s is taken to be the value normally quoted, but during melting C_s is increased by $HF/\Delta T$.

Heat input from the fire or furnace (Qin) is composed of the three components: Convection, Radiation from fire or furnace source and radiation from peripheral ambient surroundings as described in Appendix II.

The geometric view factor (F) for the test sample to the heat source is calculated using the geometry shown below.



From a knowledge of the size of the radiating heat source and the sample to source distance, the view factor is defined as:

$$F_{f\text{-}s} = \int_{0}^{A_f} \frac{\cos^2\theta \cdot dA}{\pi \cdot R^2}$$

Heat output from the Aluminium skin (Qout), facing away from the fire or furnace, is computed from the equation:

$$Q_{out} = 1.95\cdot(T_s-T_a)^{1.25} + .08\cdot\sigma\cdot[T_s^4-T_s^4]$$

The computer programme 'MELTDOWN' has been written to predict values of melting times, using finite difference techniques, to solve the differential equation (1) above, (i.e. time for the aluminium to be completely liquified). The programme is based on a constant value of heated side emissivity which is one of the inputs to the programme.This situation then corresponds to a sooted sample test as carried out using the Faverdale test furnace.

Figure A1 below summarises the measured burnthrough times with various combinations of thicknesses and emissivities of aluminium panel using the Faverdale furnace, together with the predicted times as calculated by the computer programme MELTDOWN.

Where surface emissivity is constant, equation (1) can be rearranged to show that

Burnthrough time/Plate thickness = Function (Emissivity)

and therefore a graph of burnthrough times/plate thickness versus emissivity should all lie on a single line. Figure A2 is such a graph to show the tested values of time/thickness versus emissivity together with the line calculated from MELTDOWN predictions. This graph shows there to be a good correlation between predicted and test values.

Thickness of Plate (mm)	*Measured Emissivity (E)*	*Burnthrough Times (secs)*	
		Tested	*Calculated*
0.9	0.41	27	26.9
0.9	0.64	24	19.3
1.6 (painted)	0.53	36	39.6
1.6 (painted)	0.90	30	26.4
2.0	0.08	223	152.9
2.0	0.25	97	83.7
2.0	0.64	43	42.9
1.6	0.08	118	122.3
1.6	0.25	57	67.0
1.6	0.50	39	41.3
1.6	0.70	32	32.1
1.6	0.93	31	25.8

Figure A1 Comparison of predicted and tested burnthrough times

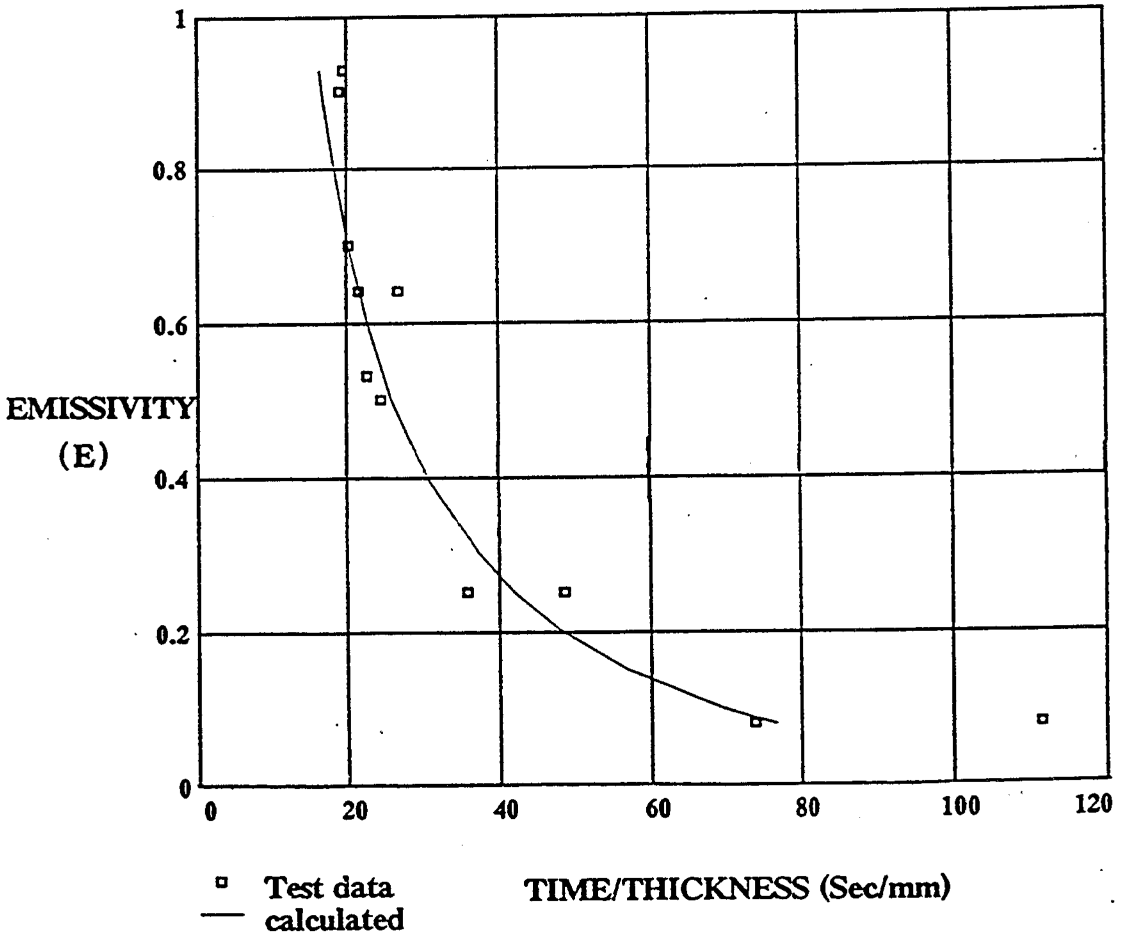


Figure A2 Correlation of emissivity and burnthrough time/thickness

The programme MELTDOWN, as stated above, is based on the heated side having a constant emissivity, and includes a short algorithm to calculate the view factor. A variation of this programme has been written, MELTDOWN1, which has been modified, as below to represent the situation of a real pool fire.

(i) Take account of the variation of surface emissivity as a function of time using equation (1).

(ii) Calculation of the view factor has been omitted and a value of 1 used instead. This corresponds to a situation with a large engulfing fire.

(iii) The heating characteristic of the fire is input as an average of a radiant heat input which is converted into an equivalent flame temperature based on a flame emissivity of 1.

Data of burnthrough times in real pool fires are reported, in a draft joint CAA/FAA test report, on a series of three different skin thicknesses at 0.813, 1.6 and 2.03 mm. Burnthrough times were 30, 45 and 54 seconds respectively. Predictions of burnthrough times have been computed using MELTDOWN1 based on the average heat flux of 151.4 kW/m^2. (13.33 Btu/sq. ft sec) which is the average flux at a height of 66 inches above the fire pan. Below is a comparison table of test and predicted times:

Aluminium Skin Thickness (mm)	*Reported Burn Through (seconds)*	*Predicted Burn Through (seconds)*
0.813	30	35.8
1.6	45	57.3
2.03	54	67.8

Measurement of emissivity and time exposed to flames show a large amount of scatter (see Appendix IV). Therefore emissivity values predicted by equation (3) of Appendix IV, can only be considered as typical of what is a highly variable phenomena. Consequently actual burnthrough times will reflect this variability and cannot be expected to show a consistent fit to predicted times.

Appendix IV Relationship between Emissivity and Exposure Time to Flames

One of the factors to emerge from test work carried out with the Faverdale test furnace, which is a clean source with no smoke, is the critical importance of the emissivity of the absorbing surface. Separate sooting trials show that surface emissivity is dependent on the time that a surface is exposed to an adjacent enveloping pool of fire (see Figure A3). To make some understanding of this process and enable any prediction work to be carried out, a function of emissivity with time exposed is needed. The approach adopted here is to assume that the rate of soot deposition is such that the probability of a soot particle falling onto any specified point of exposed surface in one second is 'P'. Causing that points emissivity to change from Eclean to Esoot. Then the probability of any point remaining at Eclean is (1–P), and the probability of any point remaining at Eclean for a period of t seconds is (1–P)*(1–P), t times.

After t seconds then:

> a proportion $(1-P)^t$ of the total area remains at an emissivity of Eclean whilst the rest has been converted to an emissivity of Esoot. ie:
>
> a proportion $1-(1-P)^t$ of the total area is at an emissivity of Esoot

The effective emissivity (E_{eff}) can then be defined as below:

$$\begin{aligned} E_{eff} &= [1-(1-P)^t]\cdot \text{Esoot} + (1-P)^t\cdot \text{Eclean} \\ &= \text{Esoot} - (1-P)^t\cdot(\text{Esoot-Eclean}) \end{aligned}$$

Results of measurements of emissivity of aluminium sheets taken during the sooting trials, range from 0.08 for clean samples to a maximum of 0.95 for a well sooted example. Taking these values to be representative for Eclean and Esoot then

$$\begin{aligned} E_{eff} &= 0.95 - (1-P)^t\cdot(.95-.08) \\ &= 0.95 - 0.87\cdot(1-P)^t \qquad (1) \end{aligned}$$

To derive a function for emissivity with time, a value for (1–P) is required. The value of (1–P) is derived from the set of all test results conducted as below:

from (1) by rearranging

$$\frac{0.95 - E_{eff}}{0.87} = (1-P)^t$$

Taking logarithms

$$\text{Log}\left(\frac{0.95 - E_{eff}}{0.87}\right) = t\cdot\log(1-P) \qquad (2)$$

Hence fitting a straight line from the origin, to a plot of $\log\left(\frac{0.95 - E_{eff}}{0.87}\right)$ versus t should give a straight line with slope of log (1–P).

Such a plot is shown in Figure A4 and a line fitted to the test points from which was obtained a slope

$$\log(1-P) = -0.00857$$

$$\therefore 1-P = 0.9805$$

Substituting back into (1) gives the equation for E_{eff} of

$$E_{eff} = 0.95 - 0.87 \cdot 0.9805^{t} \qquad (3)$$

Equation 3 can then be used to calculate burnthrough times in real fires. Figure A3 shows the line of this equation plotted along with the test results. The graph shows a reasonable fit to the test points which, as may be expected from such a chaotic process as a pool fire, shows a large amount of scatter.

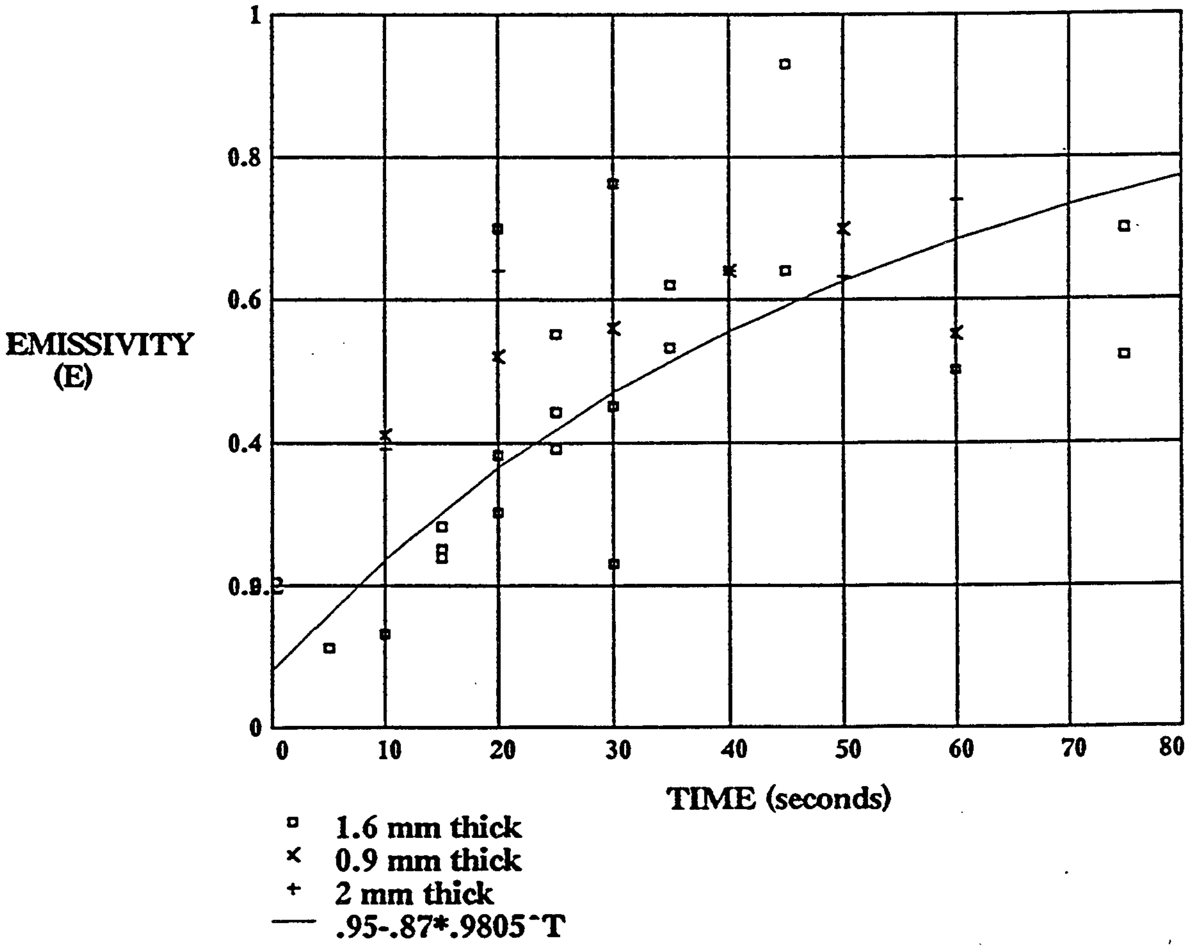


Figure A3 Emissivity versus sooting times

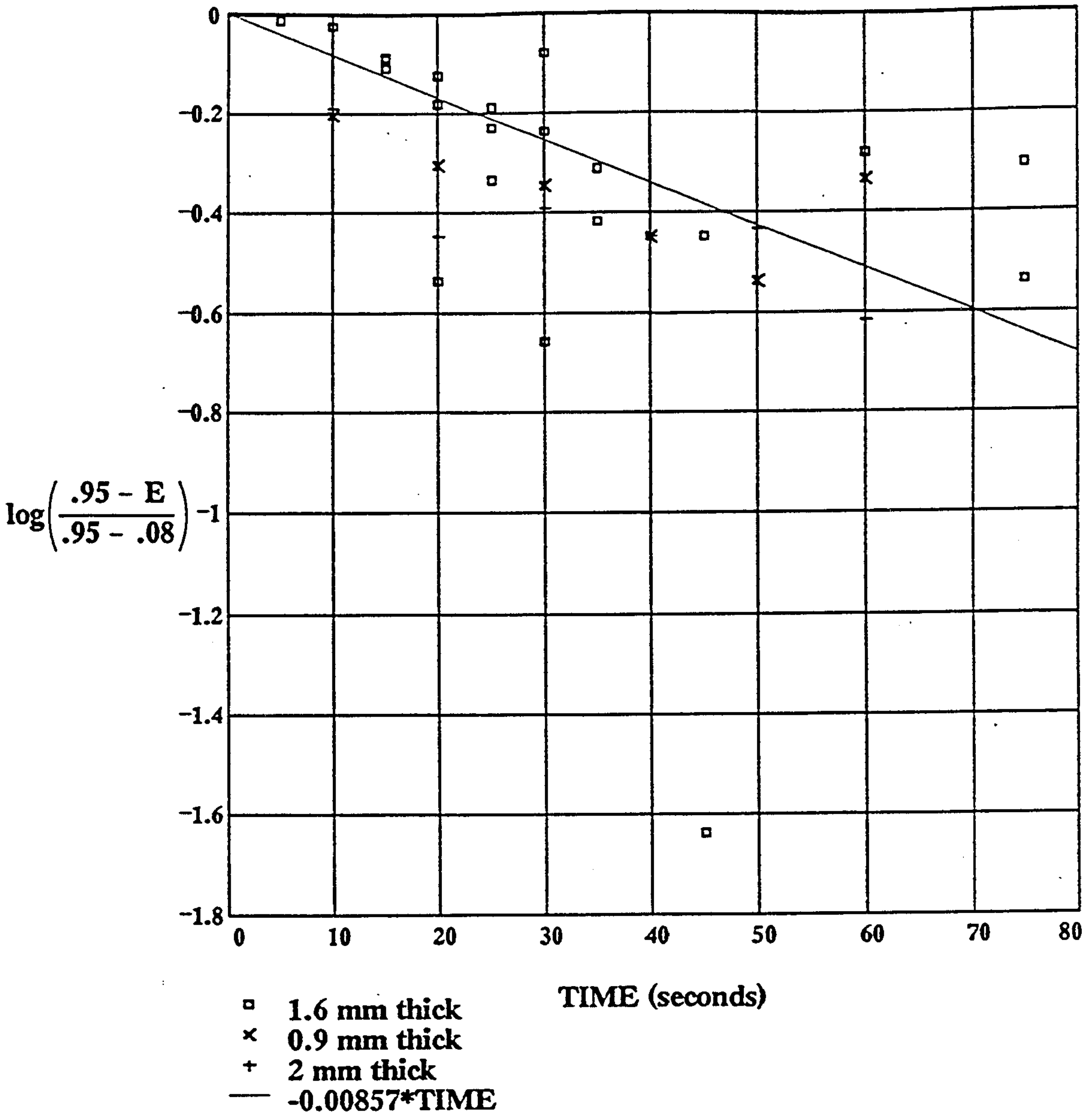
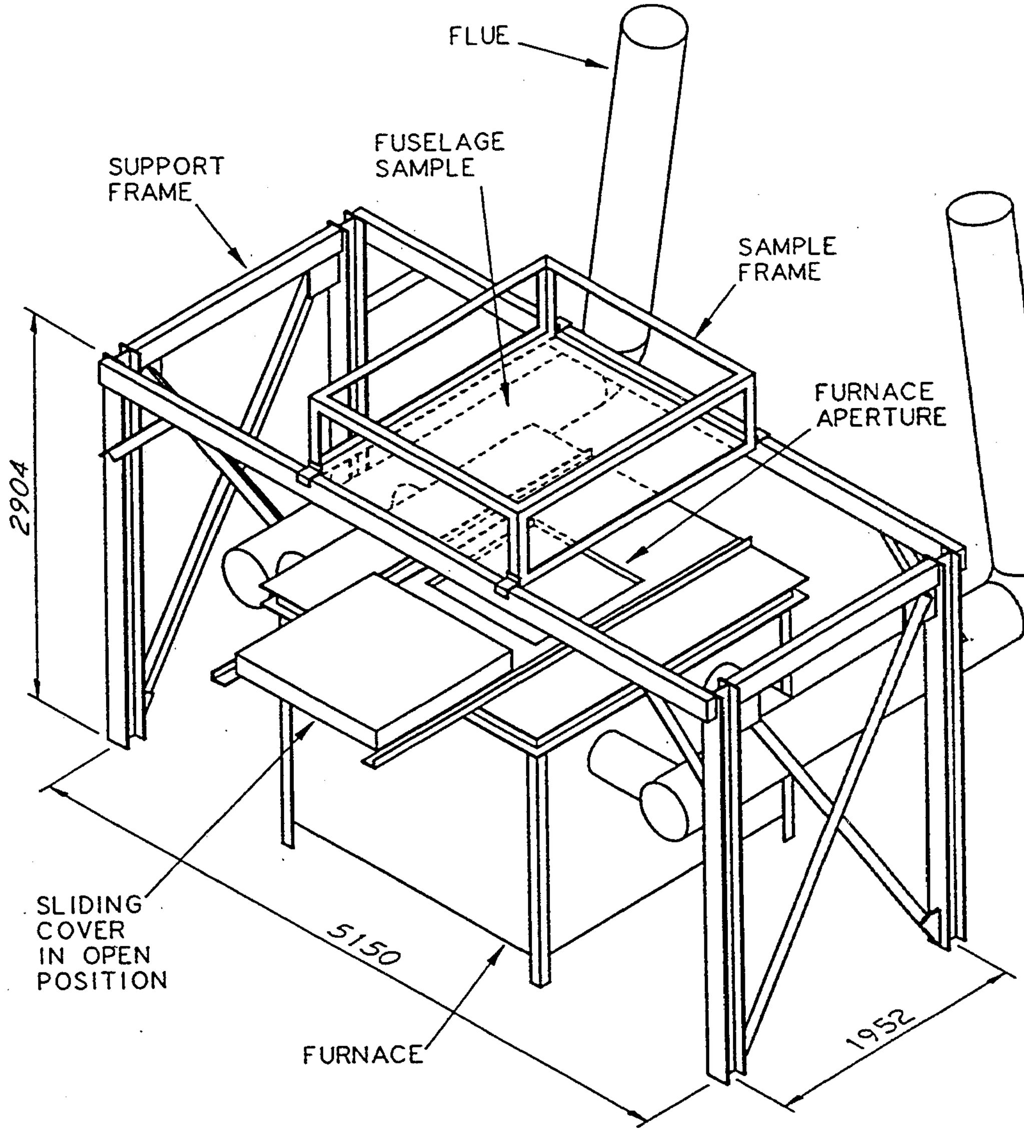


Figure A4 Derivation graph for (1–P)

Appendix V Burnthrough Test Facility



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drawn	M.H.	13.12.93	scale	customer	C.A.A.
checked	M.A.S.	14.12.93	N.T.S.	design sketch no	DSK/21-0252/20
order/enquiry no	210252			issue	A

Appendix VI Data from Commissioning Phase

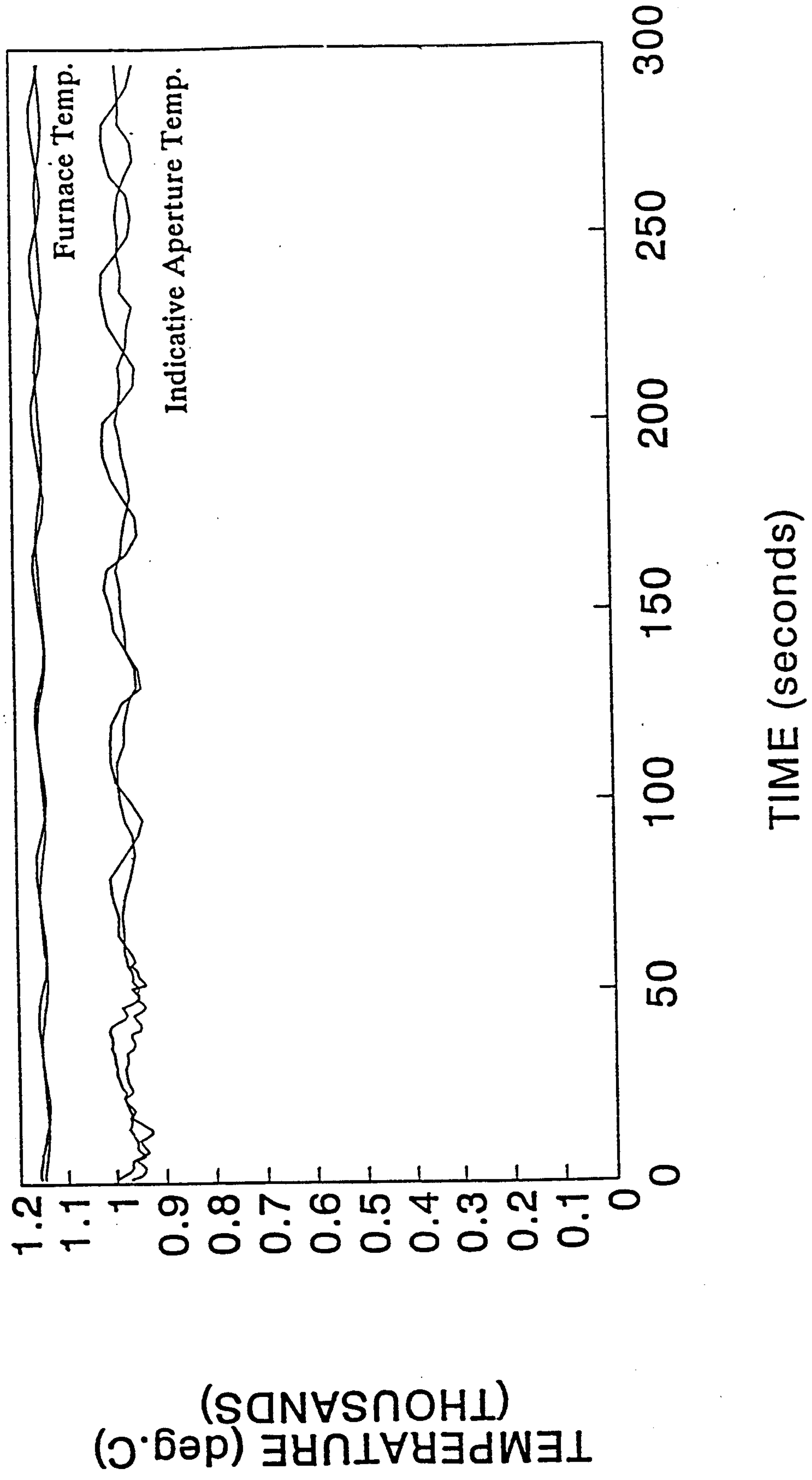


Figure A5 CAA Fuselage Fire Hardening Phase B Test 1 & 2

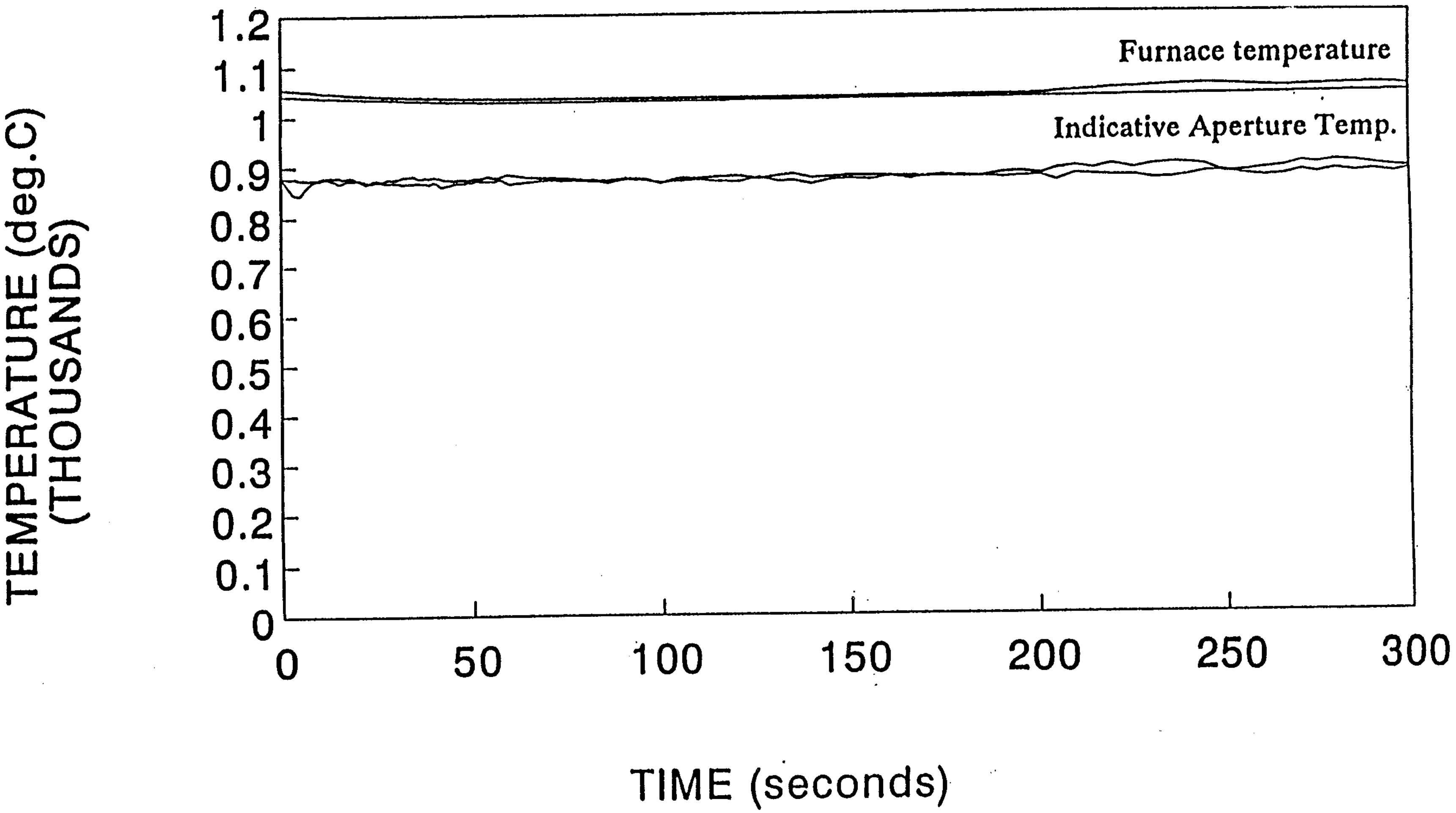


Figure A6 CAA Fuselage Fire Hardening Phase B Test 5 & 6

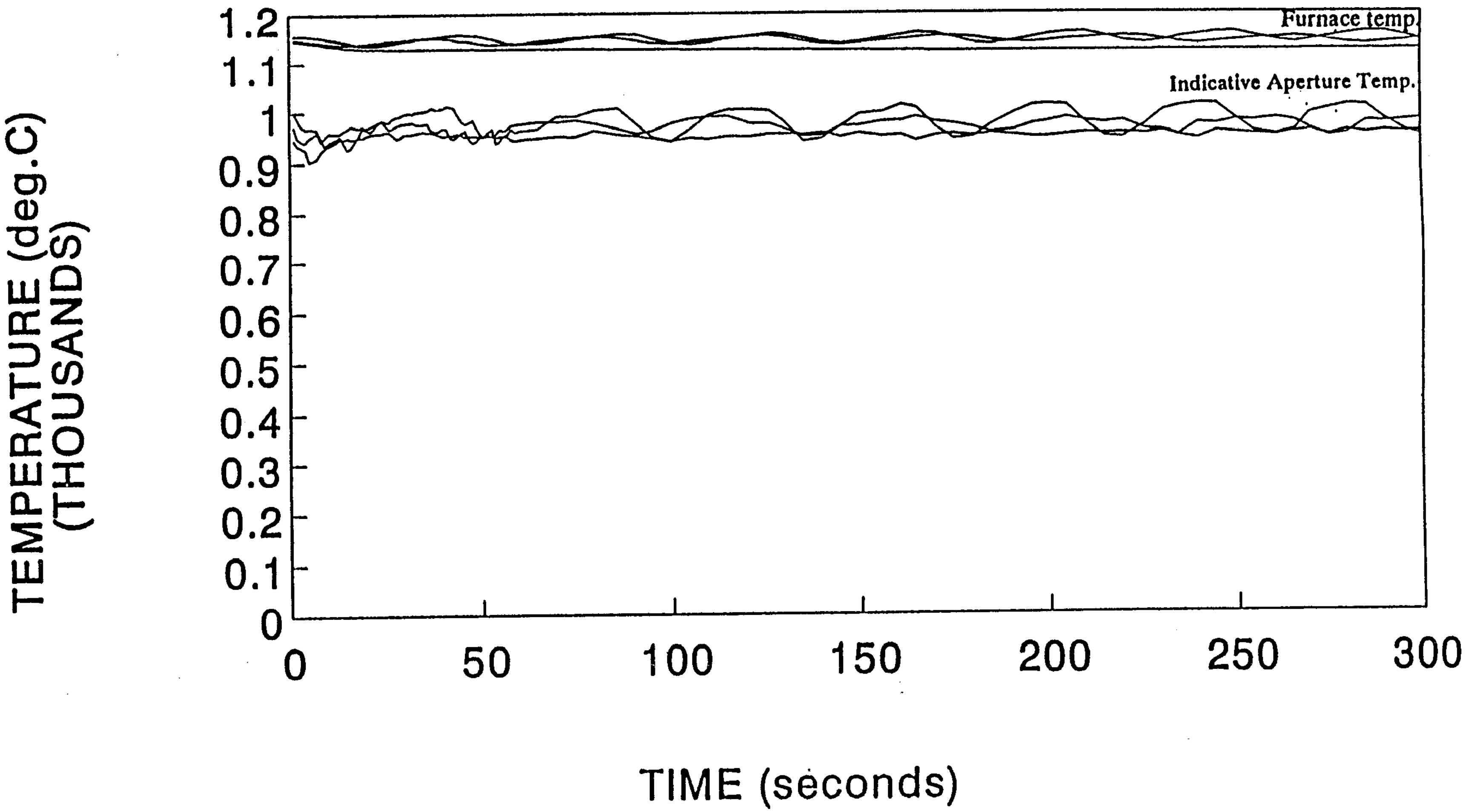


Figure A7 CAA Fuselage Fire Hardening Phase B Test 1, 2 & 11

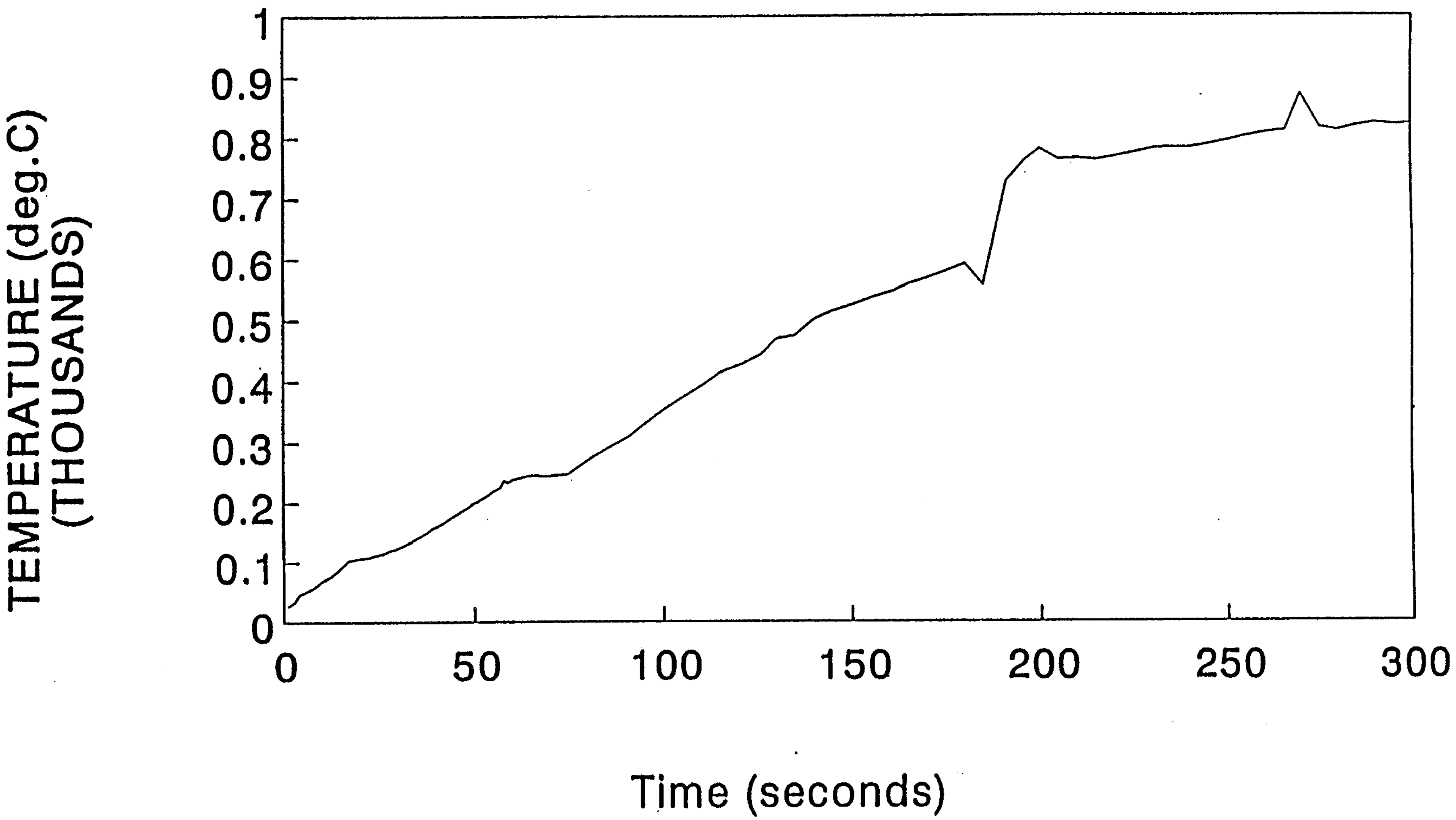


Figure A8 CAA Fuselage Fire Hardening Phase B Test 12
Sample Thermocouple Average

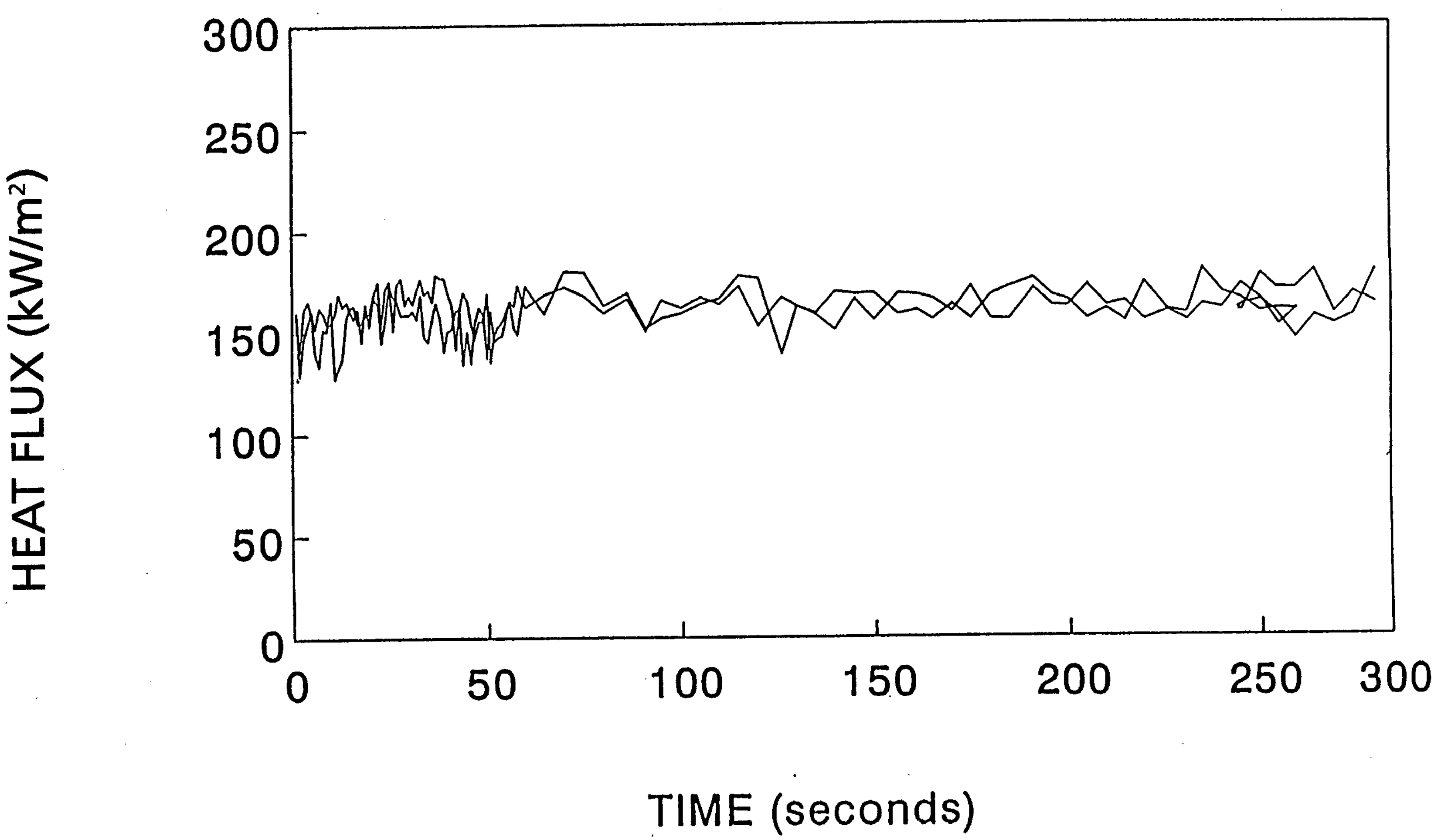


Figure A9 CAA Fuselage Fire Hardening Phase B Test 1 & 2

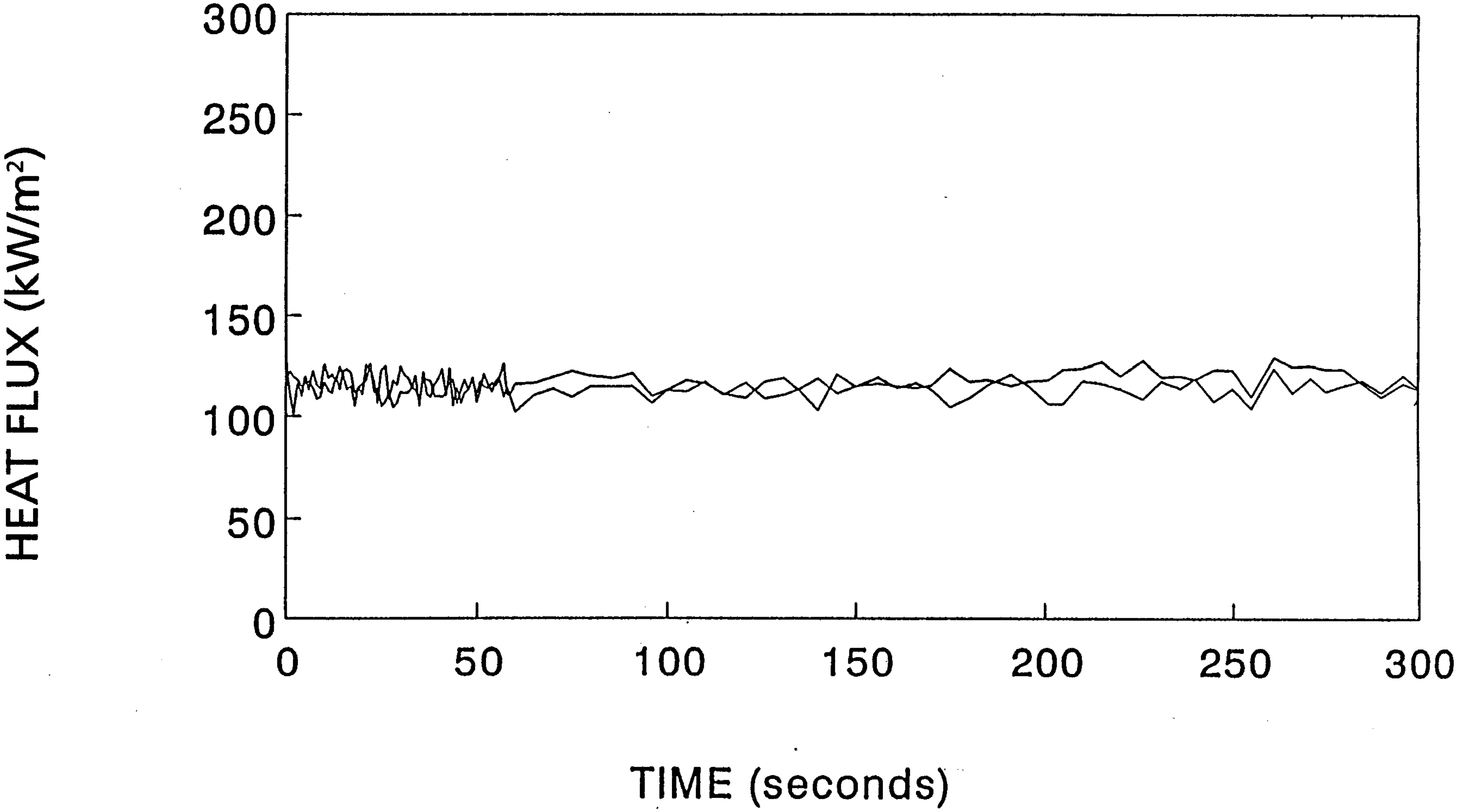


Figure A10 CAA Fuselage Fire Hardening Phase B Test 5 & 6

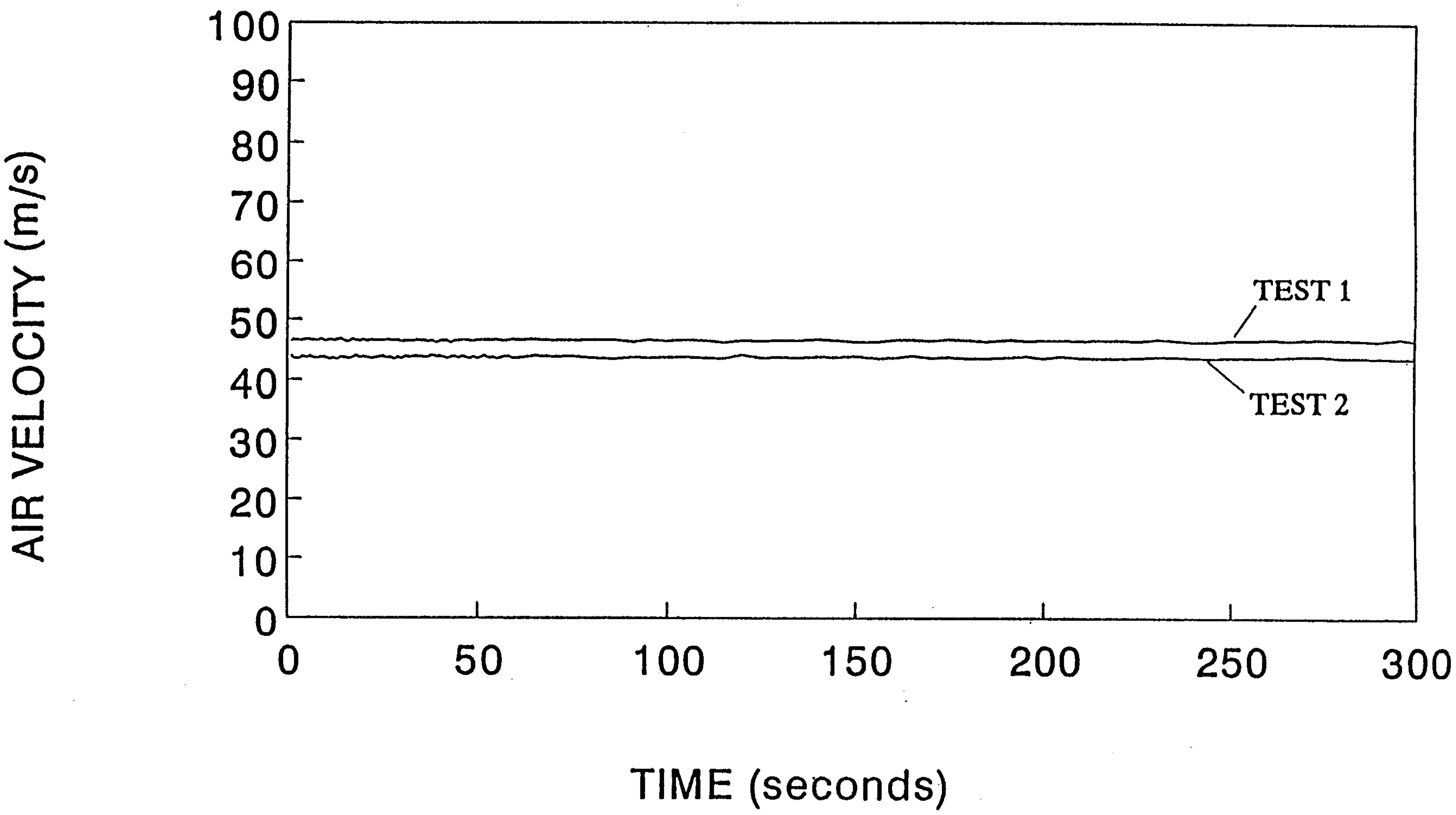
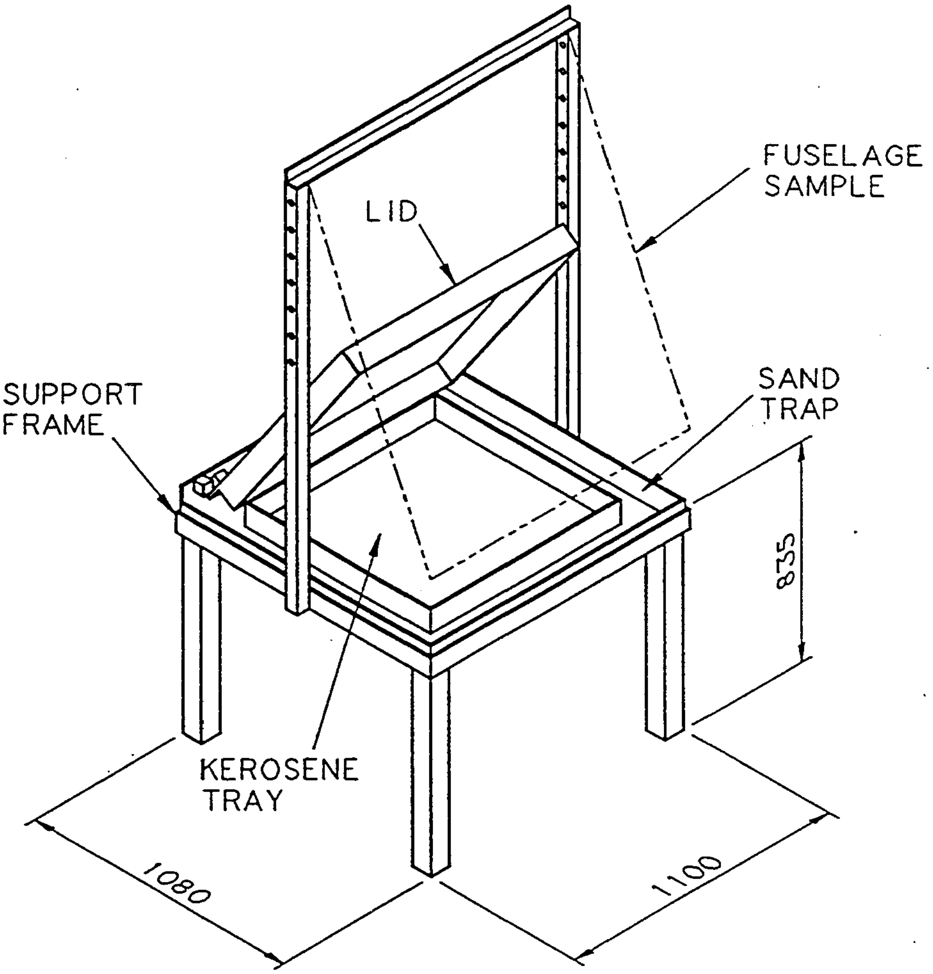


Figure A11 CAA Furnace Fire Hardening Phase B Test 1 & 2

Table A1 Soot Deposition Results (Phase B)

Soot Thickness				
Time After Fire Start (seconds)	*Average Soot Thickness (mm)*	*Upper Thickness (mm)*	*Lower Thickness (mm)*	*Average Surface Emissivity*
5	0.1	0.147	0.054	0.11
10	0.112	0.128	0.096	0.13
15	0.134	0.147	0.121	0.28
20	0.18	0.223	0.12	0.3
25	0.283	0.34	0.254	0.39
30	0.293	0.372	0.229	0.45

Appendix VII Hot Sooting Test Facility



FAVERDALE TECHNOLOGY CENTRE		Faverdale Technology Centre Faverdale Centre Faverdale Industrial Estate Darlington Co Durham DL3 0QL England		title ISOMETRIC VIEW OF HOT SOOTING RIG	
drawn	M.H.	13.12.93	scale	customer C.A.A.	
checked	M.A.S.	14.12.93	N.T.S.	design sketch no DSK/21-0252/22	issue A
order/enquiry no	210252				

Appendix VIII Data from Sooting Investigations

Table A2 Soot Deposition Investigation Coarse Sweep

Soot Thickness					
Sample Number	*Time After Fire Start (seconds)*	*Average Soot Thickness (mm)*	*Upper Thickness (mm)*	*Lower Thickness (mm)*	*Average Surface Emissivity*
15	15	0.324	0.368	0.348	0.25
16	30	0.334	0.408	0.221	0.76
22	45	0.457	0.517	0.398	0.64
23	60	0.263	0.282	0.243	0.5

Table A3 Soot Deposition Investigation Fine Sweep

Soot Thickness					
Sample Number	*Time After Fire Start (seconds)*	*Average Soot Thickness (mm)*	*Upper Thickness (mm)*	*Lower Thickness (mm)*	*Average Surface Emissivity*
25	20	0.29	0.371	0.22	0.38
26	25	0.113	0.181	0.055	0.44
27	35	0.314	0.381	0.2	0.62

Table A4 Soot Density Measurements Coarse Sweep

Sample Number	*Sooting Time (seconds)*	*Soot Covering*	*WT with Soot (mg)*	*WT minus Soot (mg)*	*WT of Soot (mg)*	*Area (cm²)*	*Soot Density (mg/m²)*
15A		> 10%	43349.33	43340.75	8.58	157.9	543.3
15B	15	90%	42668.01	42660.09	7.92	137.9	574.5
15C		90%	41527.44	41523.06	4.38	109.6	399.8
Average							505.9
16A		Full	41736.02	42729.17	6.85	117.7	582.2
16B	30	Full	41904.06	41896.7	7.36	115.6	636.9
16C		Full	43749.81	43744.2	5.61	162.6	344.9
Average							521.3
22A		Full	41022.01	41015	7.01	98.7	709.2
22B	45	Full	41477.11	41469.08	8.03	99.5	807
22C		Full	40415.88	40409.86	6.02	96.9	621.2
Average							712.5
23A		Full	42989.33	42983.75	5.58	136.3	409.3
23B	60	Full	42076.87	42072.31	4.56	120.4	378.7
23C		Full	42053.02	42047.85	5.17	117.4	440.4
Average							409.5

Table A5 Soot Density Measurements Fine Sweep

Sample Number	*Sooting Time (seconds)*	*Soot Covering*	*WT with Soot (mg)*	*WT minus Soot (mg)*	*WT of Soot (mg)*	*Area (cm^2)*	*Soot Density (mg/m^2)*
25A		20%	40383.46	40379.75	3.71	108.1	343.2
25B	20	Full	41842.36	41835.36	41835.82	6.54	578.2
25C		90%	42242.83	42237.36	5.47	125.2	436.9
Average							452.8
26A		< 10%	42683.04	42681.94	1.1	128.4	85.7
26B	25	> 90%	53117.57	43113.53	4.04	142.8	282.9
26C		> 90%	43535.56	43532.34	3.22	155.8	206.7
Average							191.8
27A		Full	41753.82	41749	4.82	123.5	390.3
27B	35	Full	42112.39	42106.71	5.68	117.4	483.8
27C		Full	41575.62	41568.9	6.72	113.2	593.6
Average							489.9

Table A6 Initial Investigation Emissivity Results

Test Date	*Sample Number*	*Test Duration (seconds)*	*Emissivity*
28.4.93	15	15	0.25
	16	30	0.76
	17	45	0.93
	18	60	0.5
	19	75	0.7
29.4.93	20	15	0.24
	21	30	0.23
	22	45	0.64
	23	60	0.5
	24	75	0.52
13.5.93	25	20	0.38
	26	25	0.44
	27	35	0.62
14.5.93	28	20	0.7
	29	25	0.55
	30	35	0.53

Table A7 Initial Burnthrough Results

Sample Number	*Sooting Time (seconds)*	*Emissivity*	*Burnthrough Time (seconds)*
Plain Aluminium	0	0.08	118
20	15	0.25	57
24	75	0.5	39
19	75	0.7	32
17	45	0.93	31

Table A8 Additional Investigation Emissivity Results

Material	*Sample Number*	*Test Duration (seconds)*	*Emissivity*
0.9mm Aluminium	31	0	0.08
	31	10	0.41
	32	20	0.52
	33	30	0.56
	34	40	0.64
	35	50	0.70
	36	60	0.55
1.6mm Painted Aluminium	37	0	0.53
	37	10	0.99
	38	20	0.98
	39	30	0.90
	40	40	0.50
	41	50	0.20
	42	60	0.32
2.0mm Aluminium	43	0	0.08
	43	10	0.13
	43A	10	0.39
	44X	10	0.25
	45X	10	0.25
	44	20	0.64
	45	30	0.60
	46	40	0.64
	47	50	0.63
	48	60	0.74
Composite Material	49	0	1.00
	49	30	N/A

Table A9 Additional Investigation Burnthrough Results

Material	*Sample Number*	*Sooting Time (seconds)*	*Emissivity*	*Burnthrough Time (seconds)*
0.9mm Aluminium	–	0	0.08	96
	31	10	0.41	27
	34	40	0.64	24
1.6mm Painted Aluminium	37	0	0.53	36
	39	30	0.90	30
2.0mm Aluminium	43CL	0	0.08	223
	44X	10	0.25	97
	46	40	0.64	43

Appendix IX Calculation of the Furnace Exit Gas Velocity

The exit gas velocity of the furnace was calculated using a mass balance technique from the following data for the 1150°C test case with a sample in place.

T_f = Furnace Temperature = 1423 K
V_i = Inlet Air Velocity = 44.8 m/s
T_a = Ambient Air Temperature = 301 K
d_i = Diameter of Inlet Duct = 0.102 m

G_g = Gas flow to burners from burners supply data sheet = 0.001 m^3/s at 170 pa supply pressure

A_e = Exit Area = 0.884 m^2

$\therefore G_a =$ Ambient Gas Flow $= \dfrac{\pi \cdot d_i^2}{4} \cdot V_i + G_g$

Correcting for temperature, exit gas velocity (V_e) is given by:

$$V_e = \frac{G_a}{A_e} \cdot \frac{T_f}{T_a}$$

$$= \frac{0.367}{0.884} \cdot \frac{1423}{301}$$

$$= 1.96 \text{ m/s}$$