STUDY REPORT

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Development of the Vertical Channel Test Method for Regulatory Control Of Combustible Exterior Cladding Systems

P.N. Whiting

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Preface

Research for the development of a reduced-cost full-scale fire test method for combustible cladding materials was conducted by BRANZ.

The aim of the Vertical Channel Test is to provide a cost-effective alternative fire test method for evaluation of the propensity for vertical flame spread on combustible claddings. Presently in New Zealand, approved test methods are the small-scale cone calorimeter or the very large and expensive full-scale tests offered only internationally.

A pre-screening method is also developed to provide a low cost alternative to vertical channel testing of cladding materials for research and development purposes.

Recommendations have been made for inclusion of the Vertical Channel Test method into the New Zealand Building Code BIA Acceptable Solutions as a suitable test method for the assessment of combustible claddings.

Acknowledgments

This work was funded by the Building Research Levy.

Note

This report is intended for regulators and code writers, Territorial Authorities, and fire engineers.

DEVELOPMENT OF THE VERTICAL CHANNEL TEST METHOD FOR REGULATORY CONTROL OF COMBUSTIBLE EXTERIOR CLADDING SYSTEMS.

BRANZ Study Report SR 137 **P.N. Whiting**

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KEYWORDS

Vertical Channel Test, Fire Test Method. Combustible, Exterior Cladding, Façade, Fire, Fire Spread

ABSTRACT

There is a potential for combustible exterior cladding systems on multi-storey buildings to support vertical fire spread up the façade. Façade fires do not initially threaten building occupants, but fire spread through the openings into upper levels may result in secondary fires which could threaten occupants.

The Australian Fire Code Reform Centre (FCRC) Project 2B–2 report contained recommendations that the Vertical Channel Test apparatus be accepted for regulatory control of the flammability of combustible cladding systems and exterior wall assemblies.

Revisions made to the New Zealand Building Code Acceptable Solutions in 2001 have called up either the relatively inexpensive small-scale cone calorimeter test, or a considerably more expensive full-scale test for the control of upward flame spread via external cladding systems. The conditions placed on cone testing do not treat all materials equally, and by default those disadvantaged materials have to be tested at full-scale. The Vertical Channel Test offers an intermediate-scale test with significant cost savings over full-scale testing while continuing to use full-size samples and construction details.

The research objective was to further the development of the Vertical Channel Test originally begun by the National Research Council of Canada (NRC) and utilise the comparative work already carried out by NRC. A series of experiments in which modifications to the fuel supply rate and the combustion chamber ventilation conditions were carried out to match the Vertical Channel Test exposure conditions to those of the full-scale CAN/ULC S134-92 (ULC, 1992) test. A greater understanding of the wall exposure conditions was gained using a plate heat flux meter to map the incident heat flux across the full width of the channel.

A pre-test screening method is proposed based on cone calorimeter test data and modelling using the BRANZfire computer program. This provides a cost-effective alternative to vertical channel testing for manufacturers conducting research and development testing.

The research concludes that the original NRC developed vertical channel could be further reduced in height without compromising the test exposure conditions. It recommends that the Vertical Channel Test, as developed and refined in this report, be included as an approved

method of test for establishing compliance with the New Zealand Building Code Acceptable Solution C/AS1 Section 7.11.2 (BIA, 2001).

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1. INTRODUCTION

The Vertical Channel Test method is an intermediate-scale test for the evaluation of surface flammability of combustible cladding and exterior wall assemblies. It was initially developed by the National Research Council of Canada (NRC) to be a cost-efficient alternative to the very large and costly full-scale tests, and has been shown to have good correlation with the larger full-scale Canadian test method CAN/ULC S134–92 (ULC, 1992).

2. BACKGROUND

The use of combustible exterior cladding systems is increasingly common on multi-storey buildings and research (Wade and Clampett, 2000) has documented the potential for these systems to support vertical fire spread up the façade. This research found that façade fires did not usually directly threaten building occupants, but that fire spread through the openings into upper levels may result in secondary fires which could threaten occupants.

There have been relatively few cases of extensive external vertical fire spread involving combustible claddings, and even fewer cases where such spread has significantly compromised life safety. Part of the reason for this could be due to the historical use of non-combustible materials on façades as is required by many building codes around the world. The small number of documented examples should therefore not be taken to mean that combustible claddings present an insignificant risk.

In Australia, the Fire Code Reform Centre (FCRC) Project 2B–2 report contained recommendations that the Vertical Channel Test apparatus be accepted for regulatory control of the flammability of combustible cladding systems and exterior wall assemblies.

Recent revisions made to the New Zealand Building Code Acceptable Solutions have called up small-scale cone calorimeter data from AS/NZS 3837 (SA/NZS, 1998) for the control of upward flame spread via external cladding systems. This was based on previous work by BRANZ where small-scale data was used to predict the propensity for upward flame propagation at full-scale. This approach is satisfactory for many materials, but there are some types of composite cladding systems where it may not be adequate. For example, some aluminium clad plastic core panels appear to perform poorly at full-scale, while at bench-scale the aluminium may not melt. For this type of construction, the Acceptable Solution requires the aluminium to be removed prior to testing, resulting in a very conservative assessment.

BRANZ research (Wade and Clampett, 2000) investigated several alternative test methods for the evaluation of combustible external claddings and concluded that realistic end-use full-scale testing was the most appropriate. The report proposed that the Vertical Channel Test method be used for regulatory control of combustible exterior claddings and wall assemblies, on the basis that a satisfactory correlation with a larger-scale test already existed, and that it could be carried out at considerably less expense to industry than the larger existing full-scale tests.

The NZBC Acceptable Solution also provides an option for full-scale testing using a large façade test (NFPA 285) as an alternative to the cone calorimeter. At that time there was no suitable locally available test method to use for this purpose, however the Vertical Channel Test would now be a practical test to use.

2.1 Development of realistic based fire testing methods

Internationally, the major full-scale test methods have been CAN/ULC S134–92 (ULC, 1992) NFPA 285, the BRE full-scale test method, the Swedish full-scale façade test SP–105, and most recently ISO 13785–2 (ISO, 2002). These attempt to replicate a real fire scenario in which a fully developed compartment fire has broken out through the window with flaming incident on the building façade. Fire testing of combustible façades at full-scale enables the complete façade system to be tested; not just the panel material, but also elements of the construction system including panel edge details and the jointing system. However, the test rigs are generally very large, which limits the number of laboratories able to carry out the tests and makes the tests very expensive.

2.2 Full-scale CAN/ULC S134–92 Test

The CAN/ULC S134–92 (ULC, 1992) Test comprises a flat wall measuring approximately 5.0 m wide by 10.3 m high with no return walls. In the lower section of the wall, a window (2.6 m x 1.370 m) is the outlet for the fire plume.

The fire exposure using propane gas fuel lasted 25 minutes, comprising a five-minute gradual build-up, followed by a 15-minute period at a steady fuel supply rate, and a five-minute cool down period. The fire exposure duplicated that recorded in wood crib fires, and the 15-minute average (over the steady gas supply rate period) of the heat flux density was 45 ± 5 kW/m² measured 0.5 m above the opening, and 27 ± 3 kW/m² measured 1.5 m above the opening, on the non-combustible lining of the test facility wall. The chosen severity of fire exposure represents a wide range of fire conditions in terms of heat release rate and window dimension. The exposure was limited to a representative level, rather than seeking a "worst case scenario" in order to prevent the heat carried by the impinging flame from masking the contribution of the tested wall specimen and making the evaluation of the tested specimen very difficult. An extreme exposing plume is also of little relevance to fire spread on combustible claddings since such a plume would most likely cause spread of fire by windows, irrespective of the wall construction materials (Oleskiewicz, 1990b). The National Building Code of Canada (NRCC, 1995) in calling up this test requires the flame spread distance to be less than 5 m above the opening and the heat flux measured 3.5 m above the opening to be less than 35 kW/m².

2.3 ISO 13785–2:2002 Test

The ISO 13785–2:2002 (ISO, 2002) Test is the most recently developed full-scale façade test method. It has been internationally agreed upon and might be expected to replace the other large-scale tests available in due course. This method is based on similar principles and performance criteria to those used in CAN/ULC S134–92 m^3. The ISO test method consists of a combustion chamber with volume in the range 20–100, with an opening in the front wall (2 m wide by 1.2 m high). The height of the test facility is 4 m above the window opening, with a main façade 3 m wide. A vertically held wing façade, 1.2 m wide, is positioned to form a re-entrant angle of 90º. Any fuel can be used to produce a window flame which exposes the test specimen to a heat flux of 55 ± 5 kW/m^2 at a height of 0.5 m above the opening, and 35 ± 5 kW/m^2 at a height of 1.5 m above the top opening. Heat fluxes are measured 3.5 m above the top of the window opening, and thermocouples are installed at the top of the test specimen and at the top of the window opening. Evaluation or performance criteria are not included in the standard.

2.4 Vertical Channel Test

The Vertical Channel Test was developed by NRC to provide a more cost-effective test to the full-scale test method (CAN/ULC S134–92) than was presently accepted. The Vertical Channel Test was designed to achieve the same exposure conditions as those in the full-scale test, but with reduced width and height.

NRC conducted a series of experiments to evaluate the assessment capabilities of various alternative reduced-scale fire test methods. The test methods included:

- IMO Surface Flammability Test (a small-scale radiant panel test)
- Modified Standard Roof Deck Test (CAN4 S107, UL 790, ASTM E 108)

- Standard Tunnel Test (CAN4 102/S102.2)
- Vertical Channel Test.

Of these, only the Vertical Channel Test results were found to correlate well with the full-scale test results (Oleskiewicz, 1990b). This research compared results from tests carried out using the full-scale and vertical channel facilities for a range of combustible cladding systems and materials, including vinyl and aluminium sidings, flame retardant plywood, composite panels and external insulation and finish systems (EIFS). The results demonstrate a good correlation between the full-scale and Vertical Channel Test methods for both the maximum flame spread distances recorded, and the maximum one-minute averaged heat flux density recorded at 3.5 m above the window.

The vertical channel offers a more cost-effective test method than the traditional full-scale alternatives by limiting the width of the specimen. It continues to test full-scale assemblies, however the test facility is of a scale that is more readily accommodated within most fire test laboratories. The Vertical Channel Test was then chosen by BRANZ to be developed further for proposed adoption in regulatory use in the assessment of combustible façade cladding materials.

3. THE VERTICAL CHANNEL TEST

The purpose of this study was to continue the development work begun by NRC, to document the test procedure and standardise the parameters required to achieve the exposure conditions in line with the NRC conclusions, and the guidance provided in the draft test method produced by ASTM (ASTM, 1992). The specific parameters studied are the dimensions of the air intake and flame outlet window openings in the fire source combustion chamber, the gas flow rate, and a further reduction in the overall height of the test rig.

The Vertical Channel Test rig constructed at BRANZ followed the NRC design comprising significant reductions in the overall dimensions from the original CAN/ULC S134–92 test. The dimensions of the test specimen were reduced from a width of more than 6000 mm to 800 mm, and the height from originally more than 9000 mm to 7320 mm. Details of the construction are provided in Appendix A. The combustion chamber window opening was correspondingly reduced, but made the same width as that of the specimen. To compensate for the reduced scale of both specimen and window opening, vertical projections were added forming a channel to enhance the fire exposure conditions on the specimen. It was found that the vertical projections increased heat transfer to the façade. They restricted lateral air entrainment to the plume causing a vertical extension of the combustion zone within the plume. The channel arrangement was reported (Oleskiewicz, 1990a) to achieve a 50% increase in the density of heat flux to the wall above the window opening over that received by the same wall without the vertical projections.

4. INCIDENT HEAT FLUX

The experimental work carried out by NRC (Oleskiewicz, 1990b) concluded that the level of thermal exposure to an exterior wall from fire venting through a window was equally influenced by the following factors:

1. The fire heat release rate
2. Window dimensions
3. Façade geometry.

Only a variation in the height of the façade was studied here; the width was considered to be fixed by the rig construction and the correlation work already carried out by NRC.

The method for measuring the heat flux exposure conditions prior to wall samples being tested comprised of two single water cooled heat flux meters. The heat flux meters used were calibrated Medtherm Series 64 total heat flux meters with a range of 0 – 200 kW/m² and calibration uncertainty of ± 2%. The two heat flux meters were placed on the centre line of the wall, at 0.5 m and 1.5 m above the window opening. These are referred to as the "calibration locations". The heat flux data recorded at the calibration locations is averaged over a 20 minute period to accommodate the fluctuations inherent in flaming exposure.

The range of the heat flux meter was chosen to significantly exceed the expected measured values in order to reduce the error of the measurement of the convective portion of the total heat flux (Oleszkiewicz, 1989)

4.1 Propane gas flow rate

The propane gas was supplied from a bank of eight 45 kg gas cylinders connected into a single manifold and pipe to the test rig. This arrangement is designed to limit the gas take-off rate from each bottle and thereby reduce the likelihood of a gas line freezing. Mains reticulated gas supply is an acceptable alternative, but was not available at BRANZ.

An Omega FMA-2613 gas mass flow controller was installed into the gas supply line immediately before the line was split to the two burners. This flow meter is capable of controlling the mass flow rate of gas across the range of 0 and 1000 SLPM (approx 0 to 33 g/s of propane gas) ± 0.5% of full-scale.

4.1.1 Experimentation

The draft ASTM test standard (ASTM, 1992) indicates that gas flow rates in the order of 15 to 25 g/s should be considered in the calibration of the test conditions. A series of experiments were carried out to explore the impact of gas flow rates. The ventilation openings in the fire combustion chamber were fixed for this series of experiments at:

Flame outlet window opening	800 mm wide x 320 mm high
Air intake opening	800 mm wide x 590 mm high.

Several gas flow rates from 15 to 20 g/s were examined and are illustrated in Figure 4-1.

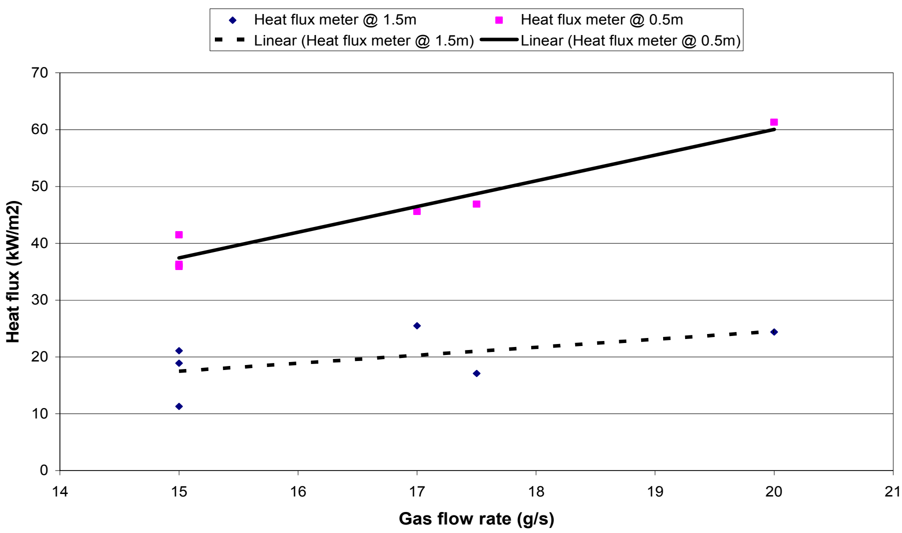

Figure 4-1: Graph of heat flux vs gas flow rate for fixed ventilation conditions.

Figure 4-1 indicates a divergent trend in the heat flux measured at the two calibration locations as the gas flow rate is increased. As the gas flow rate is increased, more of the combustion occurs outside of the combustion chamber leading to higher heat flux levels recorded at the lower calibration point. The corresponding heat flux levels recorded at the upper calibration point also increase with the gas flow rate, albeit at a slower rate. This would suggest that as the gas flow rate increases, the velocity of the combustion gases exiting the chamber also increases, leading to a reduction in the attachment of the fire plume to the wall surface.

Gas flow rates in the range 20 g/s to 25 g/s were not considered, as the exposure conditions on the specimen wall of the channel exceeded those required to match the full-scale test facility exposure conditions at one or both of the calibration points.

4.2 Combustion chamber ventilation openings

The original research done at NRC indicated that having two openings, one for air intake and the other for flame outlet, was preferable over one window-like opening. A single opening was causing cyclical pulsations of the flame due to inherent instability of combustion within a chamber having a single opening. A random pulse of the flame would decrease the area available for air intake, resulting in a decrease in flame size. This in turn would allow more air into the chamber, causing the flame to increase, and the cycle would be established. Separating the air intake from flame outlet by the central barrier panel decouples those flows and makes the flame relatively stable.

The combustion chamber comprises a steel box measuring 800 mm wide by 1500 mm deep and 1900 mm high. The interior of the chamber is lined with a 20 mm thick fire resistant low density (nominal density 100 kg/m³) mineral fibre blanket. The lining is critical to limit the fire heat losses within the combustion chamber and protect the chamber construction. Fire bricks 100 mm thick line the floor of the chamber under the burners.

The front of the combustion chamber is one of the short walls and comprises two openings separated by a steel barrier approximately across the centre portion. The lower level opening provides an air intake to supply the combustion chamber, while the upper level opening simulates a window opening and provides an outlet for the flames. Part of the experimentation was carried out to evaluate the impact of altering the respective heights of these openings. The width of the opening was maintained at the full width of the combustion chamber, matching that of the specimen wall to maximise flame exposure onto the wall containing the test specimen.

4.2.1 Experimentation

A series of experiments were carried out to determine the optimum combination of air intake and flame outlet opening heights to achieve the closest match of exposure conditions at the calibration locations to those recorded in the NRC full-scale tests. A constant propane gas flow rate of 15 g/s was maintained for this series of experiments. All variations to the ventilation opening heights were achieved by varying the size of the central barrier panel in the front wall of the combustion chamber, except where noted in Table 4-1.

Air intake opening heights ranging from 390 to 590 mm were evaluated against a series of flame outlet window opening heights ranging from 270 mm to 610 mm. The resultant heat flux values are the averages taken over 20 minutes from the start of each test. The results are graphically illustrated in Figure 4-2.

Table 4-1: Average heat flux exposure calibration test results for a range of ventilation openings.

Air intake opening height (mm)	Flame outlet window opening height (mm)	Heat flux at 0.5 m above window opening (kW/m²)	Heat flux at 1.5 m above window opening (kW/m²)
390*	320	31.7	14.8
440	320	60.1	23.0
440**	420	50.5	22.4
440	610	36.6	18.6
590	270	55.4	23.4
590	320	37.9	17.1
590	470	32.2	16.4

* air intake height reduced to 390 mm by blocking from the bottom of the combustion chamber.
** combination that most closely matched the full-scale (CAN/ULC S134–92) test exposure conditions.

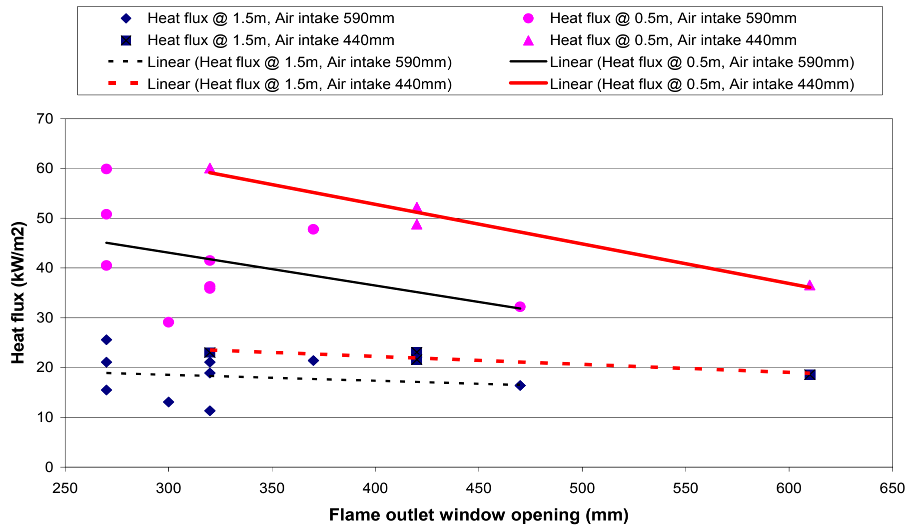

Figure 4-2: Graph of heat flux vs flame outlet window opening height for two air intake opening heights.

In Figure 4-2, the trend lines highlight the effect of reducing the air intake opening from 590 mm to 440 mm. The 440 mm high opening resulted in a significant and uniform increase in the heat flux levels recorded at the respective calibration locations for all heights of the flame outlet window opening.

In the NRC experimental work (Oleskiewicz, 1990b), a relationship was found that for a given heat release rate (gas flow rate), the window dimensions control the intensity of the fire plume and its attachment to the exterior wall. Large windows allow more fuel to be burned inside the combustion chamber than small windows allow, thus decreasing the fire plume intensity. Tall windows tend to project the flames away from the wall, thereby decreasing the heat flux exposure onto the wall. In Figure 4-2, the degree to which the flames in the fire plume are attached to the wall for a given ventilation arrangement is indicated by the proximity of the heat flux readings at the two calibration locations. The closer the two readings, the higher the degree of fire plume attachment to the wall.

The effect of increasing the height of the flame outlet window is illustrated in Figure 4-3. The increased height allows more of the combustion to occur within the combustion chamber, thereby reducing the heat flux exposure on the wall. This is consistent for different gas flow rates. A similar set of results was achieved in the second series of tests in which the air intake opening was reduced to 440 mm in height (refer to Figure 4-4).

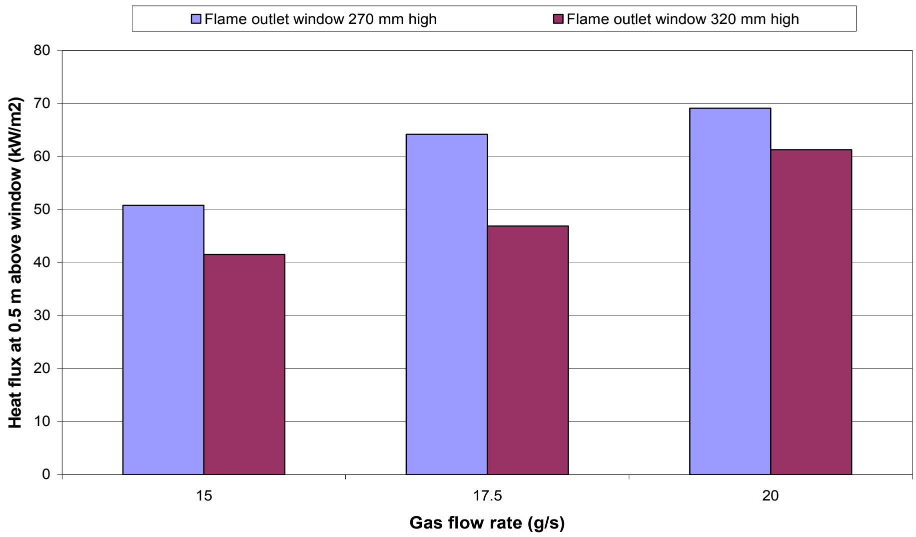

Figure 4-3: Received heat flux vs gas flow rate for two flame outlet window heights with 800 mm wide outlet and 590 mm high air intake.

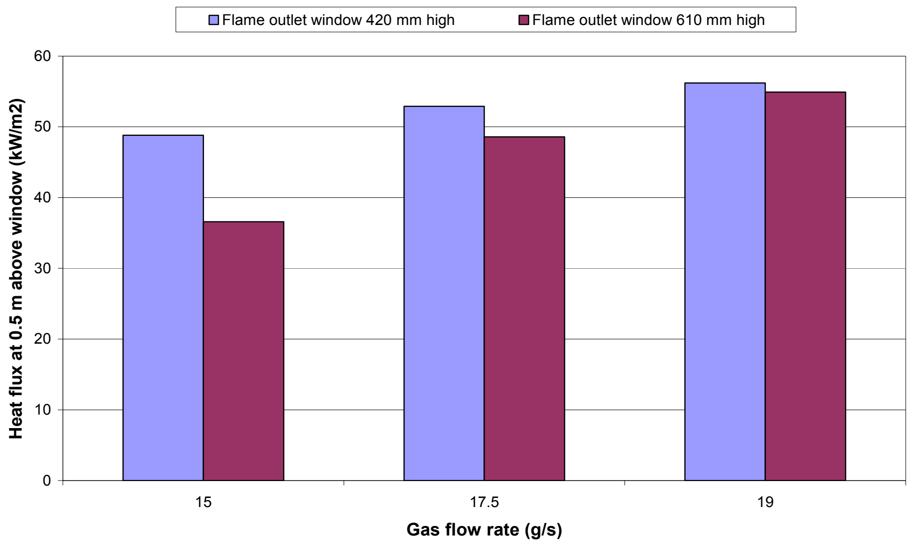

Figure 4-4: Received heat flux vs gas flow rate for two heights of flame outlet window with 800 mm wide outlet and 440 mm high air intake.

4.3 Optimum combination to achieve the full-scale test exposure conditions

The aim was to achieve heat flux exposure conditions on the vertical channel closest to matching those recorded in the full-scale (CAN/ULC S134–92) test. To achieve this, it was necessary to balance the gas flow rate with the geometry of the ventilation openings. From the results of the experiments detailed above, the key points were to keep the gas flow to a minimum to reduce the velocity of the exiting fire plume, and select the geometry of the ventilation openings to maximise combustion outside of the combustion chamber with minimum exit velocity to attain the greatest degree of fire plume attachment.

The optimum combinations were found to be provided with a gas flow rate of 15 g/s and ventilation comprising a 440 mm high air intake opening and a 420 mm high flame outlet window opening.

The flame outlet window found to provide the best fire plume attachment to the wall in the full-scale (CAN/ULC S134–92) test measured 2600 mm wide by 1370 mm high. Taking these dimensions as a ratio and scaling it down to the width of the vertical channel would result in a window approximately 420 mm high.

5. INCIDENT HEAT FLUX DISTRIBUTION MEASUREMENT

The calibration method only provides detailed heat flux data at two points. To provide a fuller description of the incident heat flux distribution across the lower portion of the wall, a plate heat flux meter was used.

5.1 Design

The plate heat flux meter was designed and developed based on that reported by Dillon (1998). The plate assembly measured 750 mm wide by 900 mm high and comprised an array of 30 thermocouples fixed at 150 mm centres to the unexposed surface of a 6 mm thick steel plate. The K-type thermocouples were made using Quiktips and fibreglass insulated 0.5 mm diameter wire. The thermocouple junction was pushed 5 mm to 10 mm through a 20 mm x 50 mm strip of 5 mm thick ceramic fibre insulation blanket to make direct contact with the unexposed surface of the 6 mm thick steel plate. The thermocouple and ceramic blanket were then covered with a strip of high-temperature mica insulation and a thin strip of steel screw fastened over using 2 mm diameter screws as illustrated in Figure 5-1.

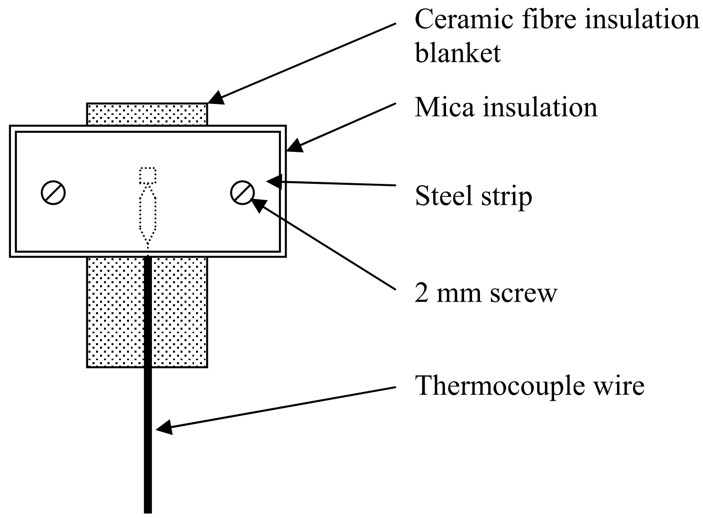

Figure 5-1: Typical plate thermocouple attachment (Dillon, 1998).

The unexposed surface of the plate was then covered with two layers of 13 mm thick ceramic fibre insulation blanket with a nominal density of 100 kg/m³ laid in strips between the rows of thermocouple wires. The direction of the strips was alternated as shown in Figure 5-2 and the entire assembly backed with a 25 mm thick ceramic fibre board (nominal density of 275 kg/m³).

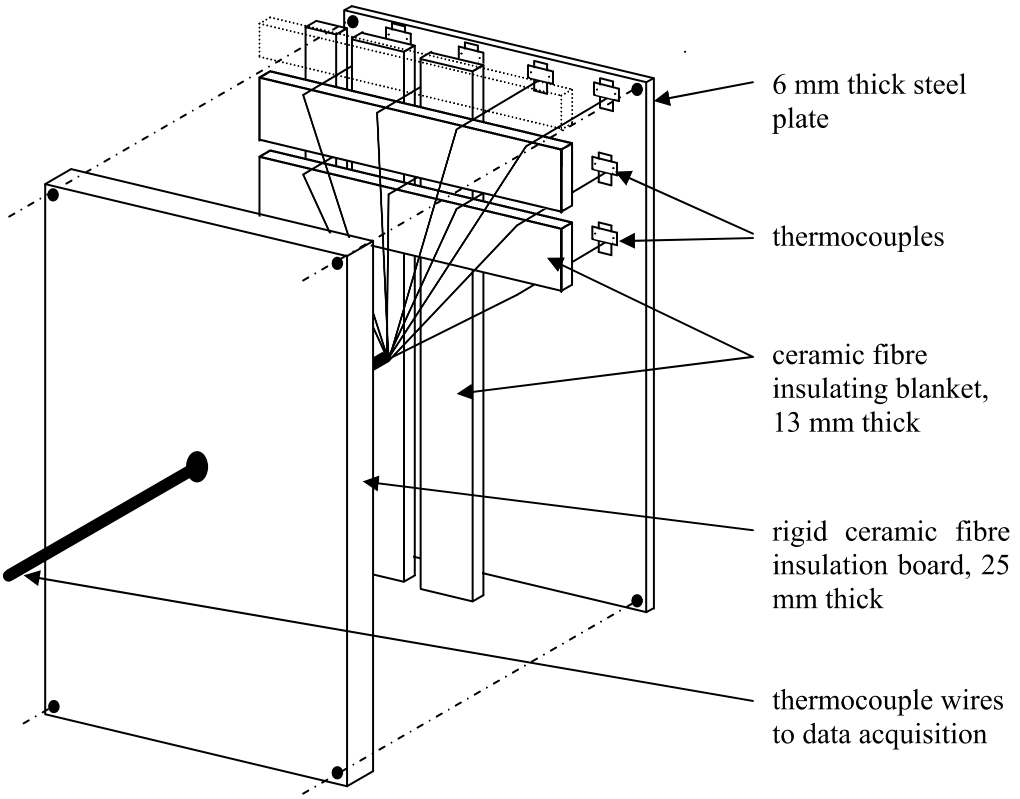

Figure 5-2: Heat flux plate assembly (Dillon, 1998).

The sampling rate for temperature readings was set at five second intervals. This comfortably exceeded the calculated thermal diffusion time for the steel plate of 2.84 seconds. The calculation methods for determining the thermal diffusion time and the heat flux incident on the steel plate is given in detail in Appendix B.

The exposed surface of the plate was painted with a high temperature matt black paint to achieve a theoretical emissivity approaching 0.97 for temperatures exceeding 500 K (Rogers & Mayhew, 1972). During testing the painted surface was damaged, but soot deposits were considered adequate to maintain the emissivity. The emissivity used in the calculations was 0.97.

5.2 Calibration

The plate heat flux meter was calibrated by comparison with one of the calibrated water cooled Medtherm heat flux meters in two identical tests. The two tests are referred to as Calibration Test 1 and Calibration Test 2. In the first test, the two Medtherm heat flux meters were positioned in the calibration locations, one each on the wall centre line at 0.5 m and 1.5 m above the window opening. In the second of the calibration tests, the plate replaced the lower Medtherm heat flux meter. The precise location of the plate was constrained by structural elements of the vertical channel. The bottom edge of the plate was then 200 mm above the window opening with the location of the single point heat flux meter corresponding to a point 300 mm above the bottom edge of the plate.

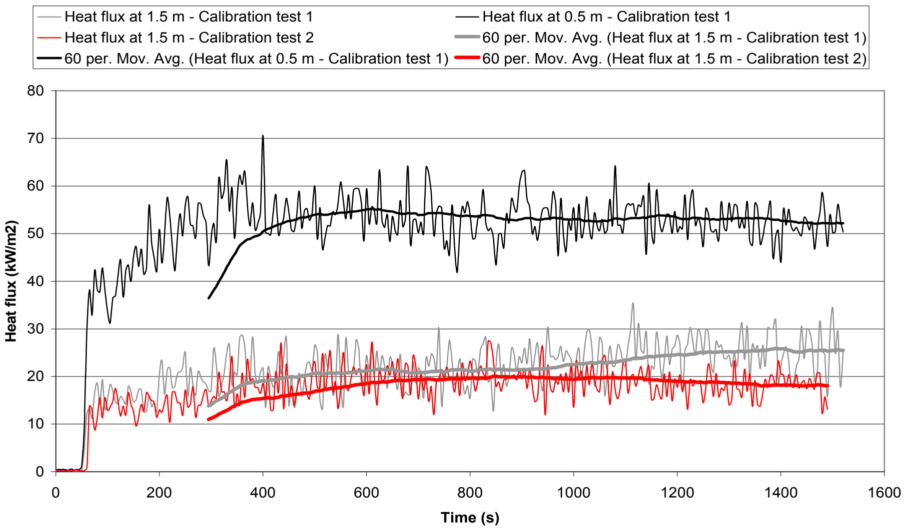

Figure 5-3: Medtherm heat flux meter measurements during calibration testing of the plate heat flux meter.

The sequence of plots (Figure 5-4 to Figure 5-7) have been taken directly from the plate heat flux meter analysis at 300 second (five minute) intervals. The heat flux is measured in kW/m², and the axes of the graph represent the array of thermocouples in six rows and five columns.

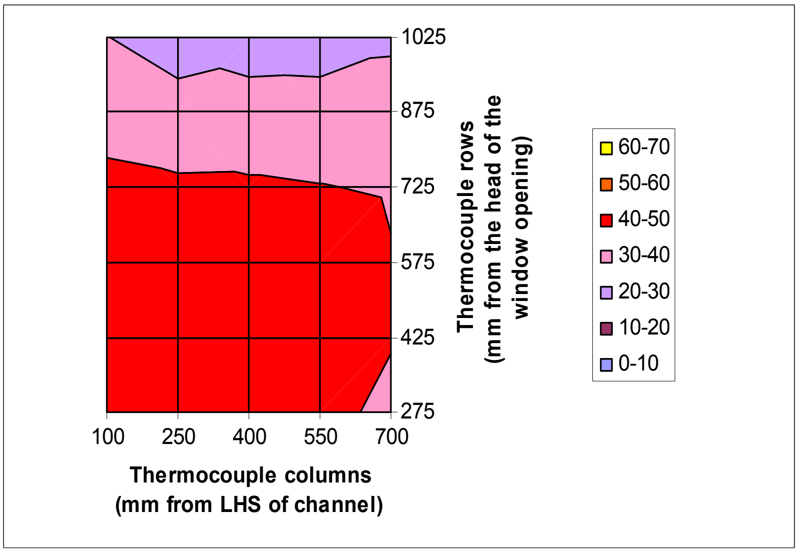

Figure 5-4: Plate heat flux meter exposure plot after 300 seconds, Calibration Test 2.

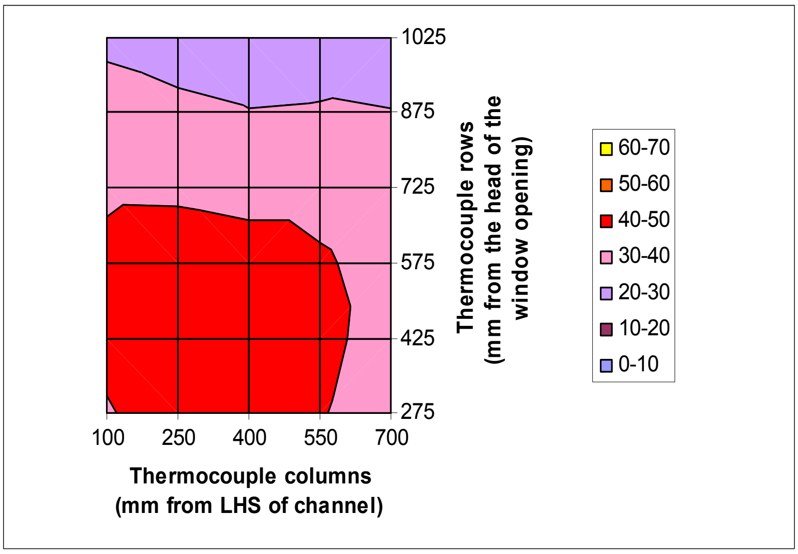

Figure 5-5: Plate heat flux meter exposure plot after 600 seconds, Calibration Test 2.

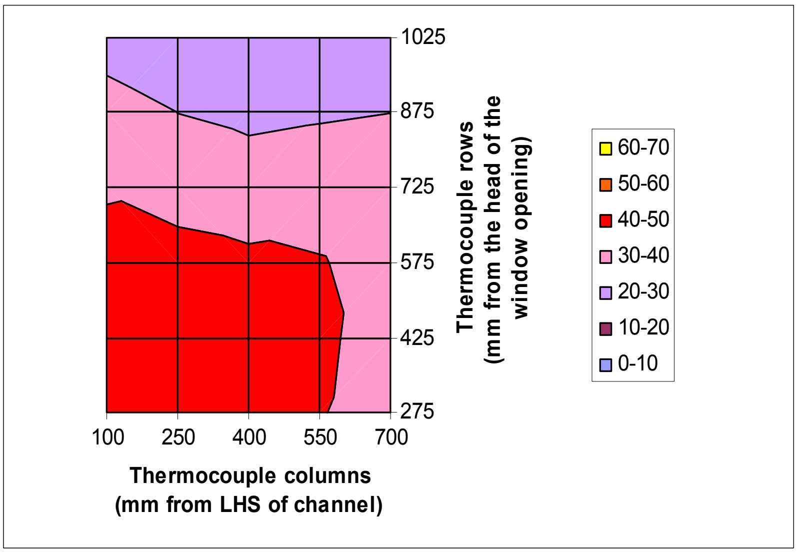

Figure 5-6: Plate heat flux meter exposure plot after 900 seconds, Calibration Test 2.

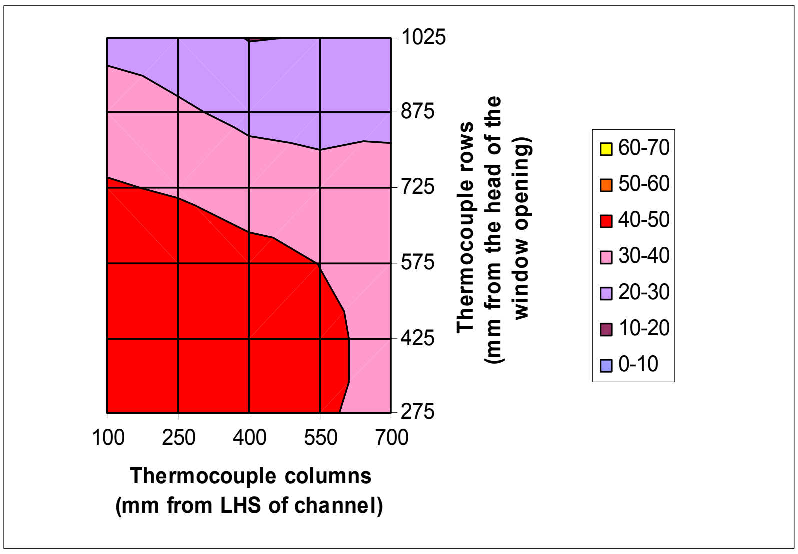

Figure 5-7: Plate heat flux meter exposure plot after 1200 seconds, Calibration Test 2.

Analysis of the plate heat flux meter data for Calibration Test 2 indicates that the exposure on the left of the specimen is marginally higher than on the right. The slight bias is evident in the 300 second interval snap-shots illustrated. In Calibration Test 1, the plate heat flux meter was located centrally between the Medtherm heat flux meters at 0.5 m and 1.5 m above the window opening. On analysis of similar data from Calibration Test 1, no bias was noted (refer Figure 5-7 and Figure 5-9).

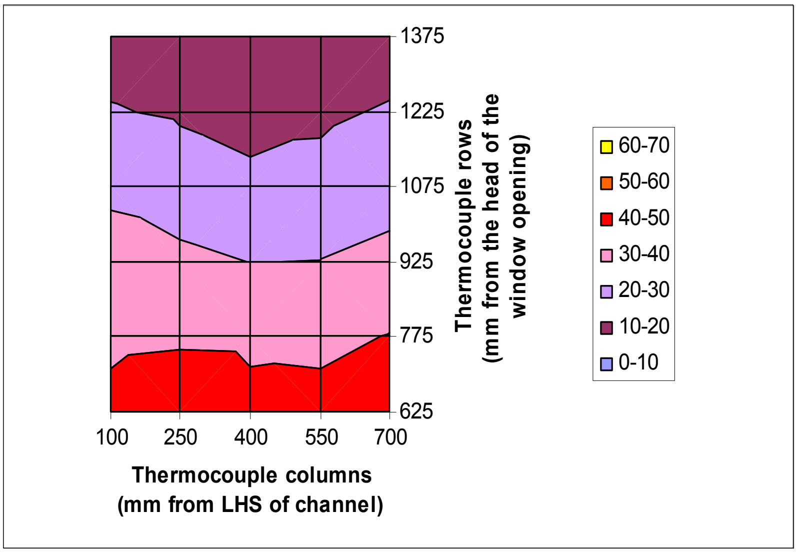

Figure 5-8: Plate heat flux meter exposure plot after 300 seconds, Calibration Test 1.

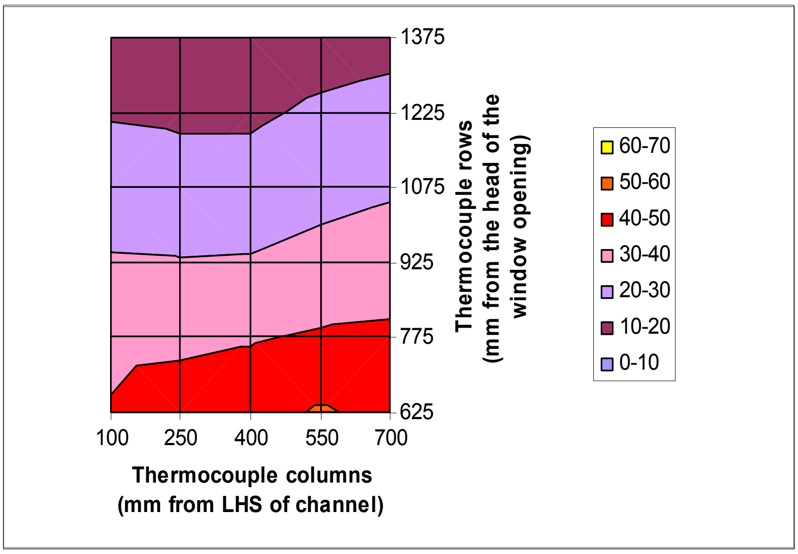

Figure 5-9: Plate heat flux meter exposure plot after 1200 seconds, Calibration Test 1

The exposure bias noted in Calibration Test 2 directly affected less than a 250 mm strip up the right of the wall. Comparison of the centre line heat flux measurements of Calibration Tests 1 and 2 found them to be consistent to within ± 3 kW/m² throughout the 20 minutes duration of the tests. The variability is within that in the specification of the full-scale CAN/ULC S134–92 test (± 5 kW/m² at 0.5 m and ± 3 kW/m² at 1.5 m above the window opening, refer Section 2.2), and therefore the calibration results were considered to be valid.

5.3 Exposure analysis

The plate heat flux meter was utilised during the series of tests carried out for evaluation of the combustion chamber openings and gas flow rates. During these tests, the plate was positioned centrally between the two water cooled heat flux meters at 0.5 m and 1.5 m above the window opening, and recessed to be flush with the back wall of the channel. This is the same location as it occupied during Calibration Test 1 referred to in Section 5.2.

The heat flux plate was found to be surprisingly responsive to changes in the exposure conditions providing detailed plots of exposure over the plate. In preliminary testing, the plate identified a bias of the fire plume towards one side of the channel that was clearly evident to observers of these tests. This bias disappeared after a couple of trial runs.

Analysis of data collected from the plate demonstrated it was capable of recording the flickering nature of heat flux measurements from flaming combustion when evaluating data recorded at five second intervals. Higher heat flux levels were often recorded off the centre line of the vertical channel wall, with extensions to the fire plume observed to be drawn further up the channel towards each side of the channel. The analysis verified the observations and highlighted the importance that two heat flux meters are positioned for testing purposes at 3.5 m above the window (refer illustrations Appendix A) to ensure that peak heat flux measurements of the fire plume were more likely to be captured.

Figure 5-10: Photograph of typical fire plume with extensions observed towards each side of the channel.

6. VERTICAL CHANNEL PRE-TEST SCREENING

The proposed Vertical Channel Test method, while cheaper and smaller in scale than the original full-scale test methods, is not best suited to conducting a series of indicative product developmental tests. It would therefore be convenient to develop a method to pre-screen potential product formulations based on small-scale cone calorimeter testing.

6.1 Present provisions in the NZBC Acceptable Solutions

The NZBC Acceptable Solutions C/AS1 7.11 provides two alternative methods to demonstrate that a combustible wall cladding system will comply with the performance requirements. One option is to use cone calorimeter test results, and the other is to have passed the full-scale test NFPA 285. The latter is a very large and expensive test, and one of the drivers for this research into a smaller and cheaper alternative (yet full-scale) test procedure.

The cone calorimeter based assessment uses the peak rate of heat release and the total heat released parameters for materials tested at 50 kW/m² over a test duration of 15 minutes. A material is classified A, B or no classification, and is respectively permitted to be used in decreasingly restrictive locations according to the classification. This is explained in more detail in Table 6-1.

Table 6-1: NZBC C/AS1 Classification of wall cladding systems based on cone calorimeter test data.

Classification	Peak rate of heat release (kW/m²)	Total heat released (MJ/m²)	Notes*
A	100	25	Able to be used in any occupancy purpose group to any building height
B	150	50	Limited to medium-rise building heights where sleeping accommodation is provided and more than 1 m from the boundary
–	No requirement	No requirement	Limited to low-rise building heights.

*Abridged for clarity from NZBC C/AS1 Table 7.5

The cone based method is ideally suited to homogenous materials and those where the jointing system is not a critical element in resisting the spread of fire. By its very nature in assessing the performance of a material based on small-scale testing (sample size 100 mm x 100 mm), the classification boundaries have been applied conservatively. It is likely then that a material marginally outside of one classification criteria will achieve a pass when tested at full-scale.

The cone based assessment method is conservative when applied to Aluminium Composite Materials (ACM). ACM panels comprise typically of a combustible core material of polyethylene or phenolic resin sandwiched between two aluminium skins. In full-scale testing, the panels are mounted vertically and the aluminium skins melt away exposing the combustible core directly to the fire. In a cone calorimeter test, the sample is horizontal permitting the aluminium skin to remain in place longer offering an increased level of protection to the combustible core. The NZBC Acceptable Solutions take this into account with the following requirement.

"Claddings incorporating a metal facing with a melting point of less than 750°C covering a combustible core or insulation shall be tested without the metal facing present." (NZBC C/AS1 C9.1.4 abridged). Aluminium has a melting point of less than 750°C.

This approach has been demonstrated to be overly conservative for some fire retarded ACM materials that have failed the cone test criteria, yet achieved a pass when tested at full-scale.

6.2 ACM small-scale fire test assessment method

A new assessment method is proposed to improve the correlation between small-scale testing using the cone calorimeter and full-scale testing. This method uses a computer based software model BRANZfire to improve the accuracy with which cone calorimeter test results can be used to assess the likely propensity for vertical flame spread on an exterior cladding system.

This assessment method is not intended to be used for regulatory control purposes; rather it is designed to be an economical method to pre-screen materials prior to conducting the more expensive larger-scale fire tests which test the complete system.

The method requires that the specimen material is tested in the cone calorimeter at three irradiance levels, say 25, 35 and 50 kW/m². This provides the software with sufficient data to determine the following parameters to characterise the material:

- heat release rate curves for each irradiance level (typically 25, 35, and 50 kW/m²)
- ignition correlation data
- thermal inertia
- heat of gasification
- critical heat flux
- effective heat of combustion.

6.3 BRANZfire environment

BRANZfire is a multi-compartment (up to 10 rooms) fire model accommodating multiple vents, and multiple burning objects. The model aims to predict various fire phenomenon in the upper and lower layers including temperature, species concentrations, plume vent flows, layer interface height, fractional effective dose, visibility and sprinkler/detector actuation. In addition, the model includes optional flame spread and fire growth models for predicting the ignition of room lining materials and adds their contribution to the fire in the room.

The modelled environment within BRANZfire attempts to approximate the actual Vertical Channel Test conditions, with dimensions of the room and ventilation openings chosen to minimise impact on the fire development. It is important to note that this application of BRANZfire is beyond the scope of its design, and that the results obtained are only to be used to judge the relative performance of each sample material.

The principle used in adapting BRANZfire for this application is to establish a very large room with a high stud, line the walls with the sample material, and place a burner against one of the walls to replicate fire impingement on the sample wall from flames issuing through a window opening. The very large room with equally large ventilation area is designed to emulate a building exterior with unlimited bounds relative to the sample being considered. Through employing a large space it will also minimise unwanted features such as the development of a hot layer influencing the flame spread rate on the sample.

The room measured 20 m wide by 20 m in length with a 10 m stud height, with ventilation provided by a wall vent measuring 20 m wide by 10 m high. The remaining walls were lined with the sample material.

6.3.1 Fire source

The burner was located against one wall, fuelled by propane and set to 800 mm in width simply to match that in the Vertical Channel Test.

The method within BRANZfire for determining the heat flux from the burner when located against a flat wall is based on work by Back et al (1994). They developed a correlation based on square propane burners against a wall. The burners varied in output from 50 to 500 kW and had edge lengths of 0.28 to 0.7 m. The maximum heat flux incident to the wall from the burner flame is given by:

$$\dot{q}''_w = E\left(1 - e^{\left(-k\dot{Q}_b^{1/3}\right)}\right)$$

where E = 200 kW/m² and k = 0.09 kW$^{-1/3}$ and $\dot{Q}_b$ is the heat release rate of the gas burner (kW). This heat flux was assumed to be constant over the wall area up to the height of the flame tip.

Based on this calculation, the heat release rate for the propane burner was set at 50 kW resulting in a theoretical incident heat flux level received by the wall of 56 kW/m². This heat flux level was considered to be a reasonable approximation of that measured on the wall above the window opening in the Vertical Channel Test.

The modelled fire was run for 20 minutes, the same as the duration of a Vertical Channel Test.

The horizontal flame spread parameter function was disabled as only the vertical orientation was to be used in this screening method.

A complete input data file has been included in Appendix C for reference.

6.4 Samples

A number of ACM samples from different manufacturers were evaluated together with some timber products. The six ACM samples included both standard grade core material (non-FR) and modified grade core materials (FR) for improved fire performance. The timber samples were included for further comparative assessment of the results obtained by the NZBC method and the BRANZfire method. In addition full-scale Vertical Channel Test results would be available from the channel height experiments done using 9 mm thick untreated plywood (refer Section 7).

6.5 Sample testing and preparation

To characterise the fire performance of the materials, BRANZfire ideally requires cone test data to be collected at a minimum of three irradiance levels, typically these are 25, 35 and 50 kW/m². The model then correlates the ignition data to determine ignition parameters which are then used in the simulation.

The ACM samples were prepared for cone calorimeter testing by removal of the aluminium metal facing on the exposed face in accordance with the BIA Acceptable Solutions C/AS1 C9.1.4. Further details of this requirement are given in Section 6.1.

6.6 Screening method

Screening is achieved using the vertical flame spread parameter, the "wall y-pyrolysis front" which is calculated within the model. A material is predicted to pass the Vertical Channel Test if the vertical flame spread parameter does not exceed two metres within 20 minutes.

6.6.1 Background to the 2.0 m flame spread parameter limit

A flame spread limit of 2.0 m was established to capture the predicted performance of the ACM Type C material. A common feature of the results is that materials that have been predicted to fail the VCT all exhibit a flame spread rate that increases exponentially throughout the 20 minutes modelled (refer to Figure 6-). The ACM Type C material exhibits the same trend, albeit at a rate considerably less than those of the other materials predicted to fail.

In the VCT, the Type C ACM only marginally failed the VCT when one of the two heat flux meters located at 3.5 m above the window opening recorded heat fluxes in excess of 35 kW/m² for 50 seconds between 427 and 479 seconds into the test and again for approximately 97 seconds between 535 and 632 seconds. A 60 second moving average trend line applied to smooth the raw heat flux data indicated that a maximum exposure of 38 kW/m² was reached. The flame spread criteria was not exceeded, with flame tips recorded no higher than 4.5 m throughout the 20 minute test. The maximum temperature recorded by the thermocouple at 4.5 m above the window was 324.5°C after 457 seconds.

6.7 Pre-screening method results

The performance predictions made using the BRANZfire based method are illustrated in Figure 6- and summarised in Table 6-1.

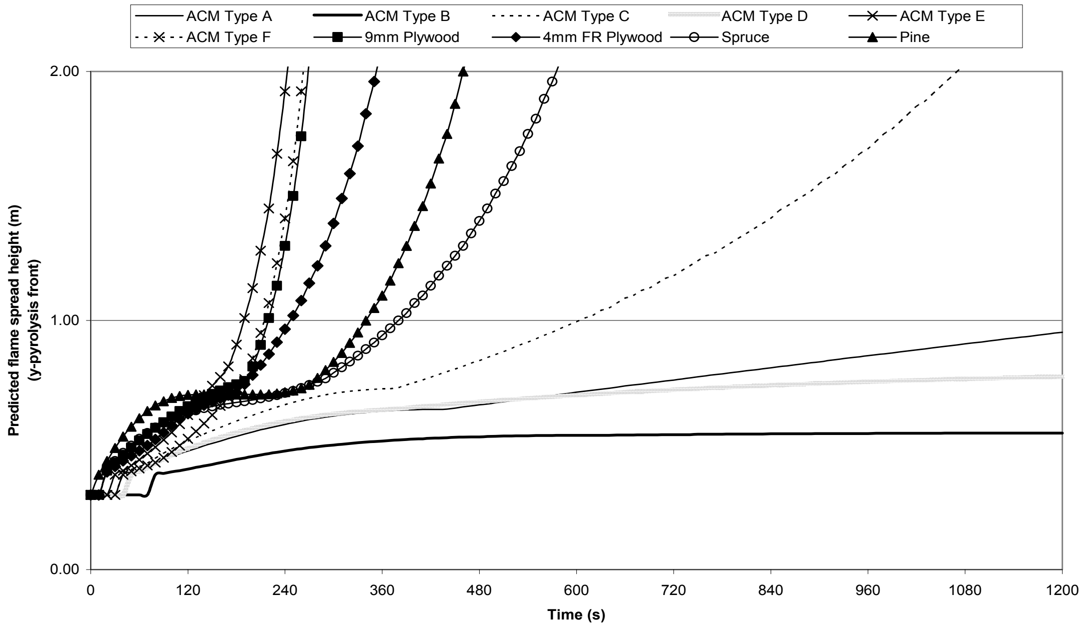

Figure 6-1: Predicted flame spread rates for several façade materials using the BRANZfire based model.

Table 6-2: Predicted Vertical Channel Test results

Material	Grade	"y-pyrolysis front" vertical flame spread height (m)	Time (s)	Predicted VCT performance (Pass/Fail)
ACM Type A (6mm)	FR	0.95	1200	Pass
ACM Type B (6mm)	FR	0.55	1200	Pass
ACM Type C (6mm)	FR	2.45	1200	Fail
ACM Type D (6mm)	FR	0.78	1200	Pass
ACM Type E (6mm)	Non-FR	2.00+	250	Fail
ACM Type F (6mm)	Non-FR	2.00+	260	Fail
Ply, untreated (9mm)*	Non-FR	2.00+	260	Fail
Ply, FR (4mm)**	FR	2.00+	360	Fail
Spruce, untreated (5mm)**	Non-FR	2.00+	580	Fail
Pine, varnished (10mm)**	Non-FR	2.00+	460	Fail

* plywood used in the full-scale Vertical Channel Tests, refer Section 7
** sourced from BRANZfire materials database files

6.8 Existing NZBC Acceptable Solution Criteria

The present NZBC Acceptable Solutions provides a method for determining the suitability of a cladding material based on cone calorimeter test data generated by samples exposed to 50 kW/m² for a period of 15 minutes. The specific criteria are described in more detail in Section 6.1. The relevant cone test data, together with corresponding NZBC C/AS1 assessments for each sample, are presented in **Error! Reference source not found.**.

Table 6-3: Present NZBC Acceptable Solution C/AS1 Table 7.5 assessment.

Sample	Grade	Peak HRR (kW/m²)	Total heat released (MJ/m²)	NZBC Acceptable Solutions C/AS1 Classification (A, B or –)*
ACM Type A (6mm)	FR	225	59	–
ACM Type B (6mm)	FR	132	35	B
ACM Type C (6mm)	FR	168	61	–
ACM Type D (6mm)	FR	193	50	–
ACM Type E (6mm)	Non-FR	382	36	–
ACM Type F (6mm)	Non-FR	507	48	–
Ply, untreated (9mm)	Non-FR	353	60	–
Ply, FR (4mm)	FR	297	41	–
Spruce, untreated (5mm)	Non-FR	166	53	–
Pine, varnished (10mm)	Non-FR	218	56	–

Refer to Table 6-1 for details.

6.9 Comparison of BRANZfire assessment with present NZBC C/AS1 assessment

Table 6-4: Comparison of assessment methods with large-scale test results.

Material	Grade	NZBC Assessment (ref Section 6.1)	BRANZfire assessment method	Larger-scale fire test results
ACM Type A (6mm)	FR	Fail	Pass	Passed NFPA 285
ACM Type B (6mm)	FR	Group B Classification	Pass	Passed VCT
ACM Type C (6mm)	FR	Fail	Fail	Failed VCT
ACM Type D (6mm)	FR	Fail	Pass	Not tested *
ACM Type E (6mm)	Non-FR	Fail	Fail	Not tested
ACM Type F (6mm)	Non-FR	Fail	Fail	Not tested
Ply, untreated (9mm)	Non-FR	Fail	Fail	Failed VCT
Ply, FR (4mm)	FR	Fail	Fail	Not tested
Spruce, untreated (5mm)	Non-FR	Fail	Fail	Not tested
Pine, varnished (10mm)	Non-FR	Fail	Fail	Not tested

* approved for certain applications having passed ASTM E 84 and BS476 Parts 6 & 7
FR fire performance modified with additives
Non-FR no additives to improve the fire performance

6.10 Conclusions

The method developed here to utilise BRANZfire and characterising cone calorimeter test data sets has been used to pre-screen six different ACM panels and a 9 mm thick untreated plywood. When reviewing the ACM assessments, the BRANZfire predictions were consistent with the results of the larger-scale testing in all three cases where the ACM's had been tested at large-scale. The NZBC C/AS1 assessment method correctly predicted two of the ACM panels, one of which being a conservative pass result with some restrictions placed on where it may be used (refer Table 6-1), and provided a conservative assessment for the third ACM product.

The timber samples were included to evaluate the BRANZfire based assessment method with a selection of materials expected to fail full-scale façade tests. The BRANZfire assessments were consistent with those made using the NZBC assessment method across all four timber samples. In addition, the predicted performance of the 9 mm thick untreated plywood was confirmed with two Vertical Channel Tests done to establish channel height requirements (refer Section 7).

The results indicate that the BRANZfire based method is capable of correctly predicting the large-scale fire test performance of ACM façade panels, while the NZBC C/AS1 assessment method is demonstrated to be conservative when applied to ACM panels.

The BRANZfire assessment method flame spread criteria threshold of 2.0 m was set to correctly capture the ACM Type C material, and this material when tested in the VCT exceeded the failure criteria only by a small margin. Based on the testing and modelling completed, it is recommended that full-scale testing should be considered for any material that is predicted using the BRANZfire method to exceed the 2.0 m flame spread criteria within the last two to three minutes.

More full-scale test data sets are required to enable this assessment method to be refined further.

7. FULL-SCALE TESTING FOR DETERMINATION OF THE TEST HEIGHT

The original draft test method specified a sample height of 7320 mm, with the total height of the test rig assembly close to that of the full-scale CAN/ULC S134–92 (ULC, 1992) Test.

A reduction in the height of the test facility would have many benefits: more test facilities would be able to accommodate and conduct tests using the equipment; the construction and testing could be carried out inside laboratories removing many of the weather-related constraints of testing outside; and construction and operational costs would be further reduced.

The maximum available reduction to the overall height of the specimen is limited by the pass/fail criteria of vertical flame spread on the specimen material to exceed 5000 mm. The 5000 mm criteria is required to maintain the correlation between the full-scale testing and that carried out on the draft vertical channel.

7.1 Full-scale Vertical Channel Tests

The evaluation process comprised calibration tests and tests in which the channel was lined with a combustible cladding. The calibration test data was sourced from the earlier calibration test series for the 7320 mm high channel, and by carrying out a further calibration run with the test facility height reduced in height to 5000 mm.

Throughout the tests, temperature measurements were recorded using 1.5 mm diameter sheathed K-type thermocouples. The thermocouples were installed from the non-exposed surface through small holes in the test specimen and positioned with approximately 12 mm of exposed bead. Thermocouples were located at 1.5 m above the window opening and thereafter at 1.0 m intervals to the top of the channel. In addition, one was placed at the top of the combustion chamber window opening for monitoring. This provided consistent data collection to permit direct comparison of the exposure conditions achieved throughout the full height of both the 7320 mm and the 5000 mm high channel.

Temperatures were recorded by the above thermocouples in two 10 minute test runs, one test run for each of the two channel heights being considered. The thermocouple data illustrated in Figure 7-1 falls neatly into pairs with negligible differences between the temperatures recorded at equivalent locations in the two channel heights. The greatest fluctuations were recorded at the thermocouples closest to the combustion chamber, at the window opening and at 1.5 m above the window opening, and occurred predominantly in the first four minutes. The consistency demonstrated by all thermocouples above 1.5 m throughout the evaluation period has led to the conclusion that reducing the height of the channel has not adversely affected the exposure conditions.

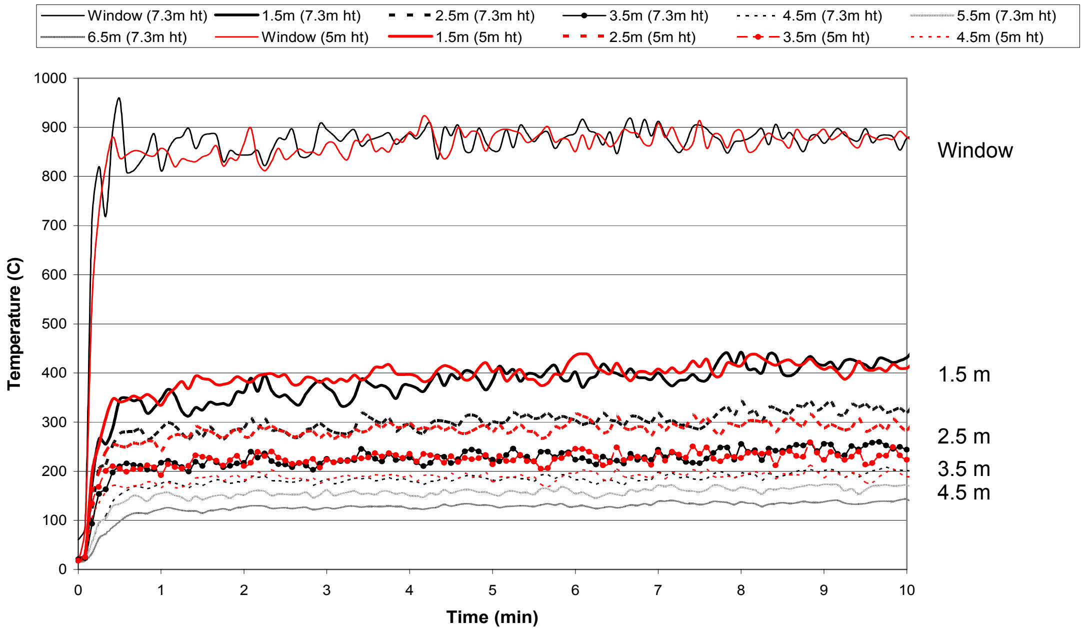

Figure 7-1: Comparison of calibration tests thermocouple data for 7320 mm and 5000 mm channel heights.

Further testing was carried out to assess if the reduction in channel height would influence the outcome of the test when lined with a combustible sheet material. Two tests were carried out, one each at the respective channel heights. In both tests the channel was lined with untreated 9 mm thick pine plywood from the same batch, pre-conditioned at 23°C ± 2°C and 50% ± 5% relative humidity. This material was predicted to exhibit flame spread (refer Sections 6.6 and 6.8), and to provide relatively good consistency in the material properties. The plywood was secured to the back wall of the channel with screws at 300 mm centres around the perimeter of each 2400 x 800 mm sheet, fixed directly onto the non-combustible channel lining board.

The tests were conducted in accordance with the test procedure (refer BRANZ Technical Recommendation TR 16: *Proposed standard test method for surface flammability of combustible cladding and exterior wall assemblies using vertical channel apparatus*), and included relocation of the heat meters to a height of 3.5 m above the window opening.

7.2 Definition of flame spread

The plywood tests permitted a comparative analysis of the data sets with regard to developing a specification for the assessment of flame spread height. The draft test standard is not clear and based the assessment on observation of the flame tip, although no formal definition was provided.

A good correlation was found to exist between the observations of flame tip extension heights, the heat flux measurements, and the temperatures recorded by the thermocouple at 4.5 m above the window opening (refer Section 7.3). It was found that one or both of the failure criteria were met when the temperature measured at 4.5 m above the window opening exceeded 500°C for at least 30 seconds. It is proposed then that this be used for determination of flame spread exceeding the failure criteria.

7.3 Test results

In Plywood Test I, the plywood specimen material lined the back wall of the channel to 7320 mm above the combustion chamber window opening. The observations made during the test are recorded in Appendix D 14.1.

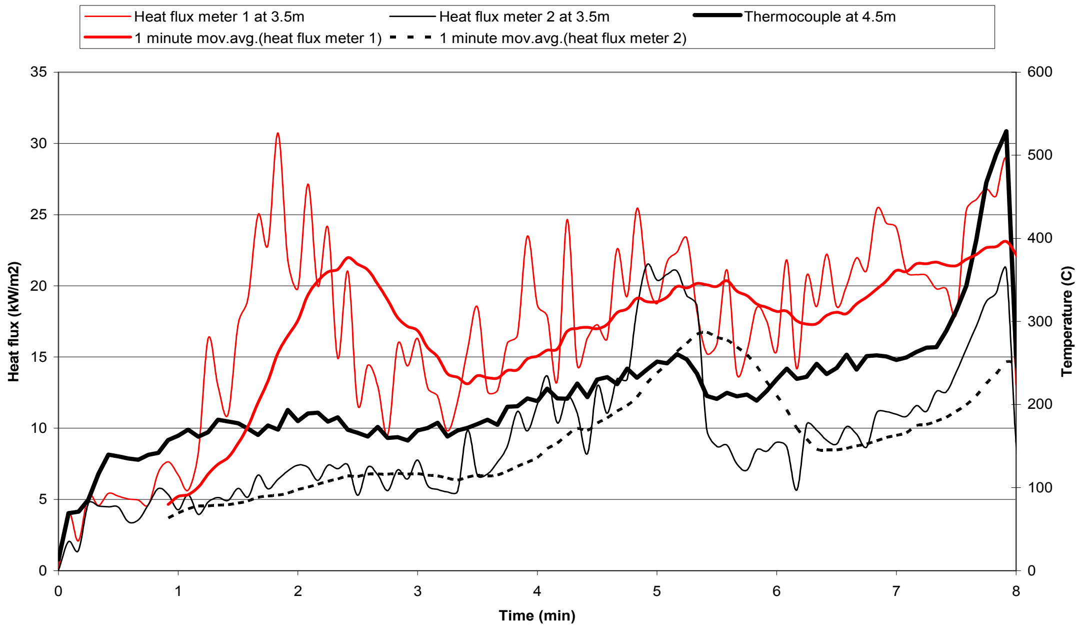

Figure 7-2: Plywood Test I heat flux at 3.5 m and temperature at 4.5 m (channel height 7320 mm).

Plywood Test I was terminated after 7 min:55 sec to prevent damage to the fire lab building. The flame spread was observed to have exceeded the 5000 mm failure criteria and was continuing at an increasing rate towards the top of the channel. Analysis of the test results (refer Figure 7-2) confirmed that the 500°C temperature threshold for failure had just been exceeded 10 seconds prior to the end of the test. The heat flux failure criteria limit of 35 kW/m² had not been exceeded during the test.

In Plywood Test II, the topmost section of the test rig structure was removed and the plywood specimen material attached to the back wall of the channel to the new height of 5000 mm.

In accordance with the test procedure, the test was deemed to have failed after only four minutes, with flame spread beyond 5000 mm as determined by the failure criteria of 500°C at 4.5 m being exceeded for more than 30 seconds after 4 min:40 sec (280 seconds) (refer Figure 7-3). The heat flux failure criteria limit of 35 kW/m² was exceeded after 4 min:20 sec (260 seconds). The reduced height enabled the test to be conducted for the required 20 minutes duration without endangering the fire laboratory.

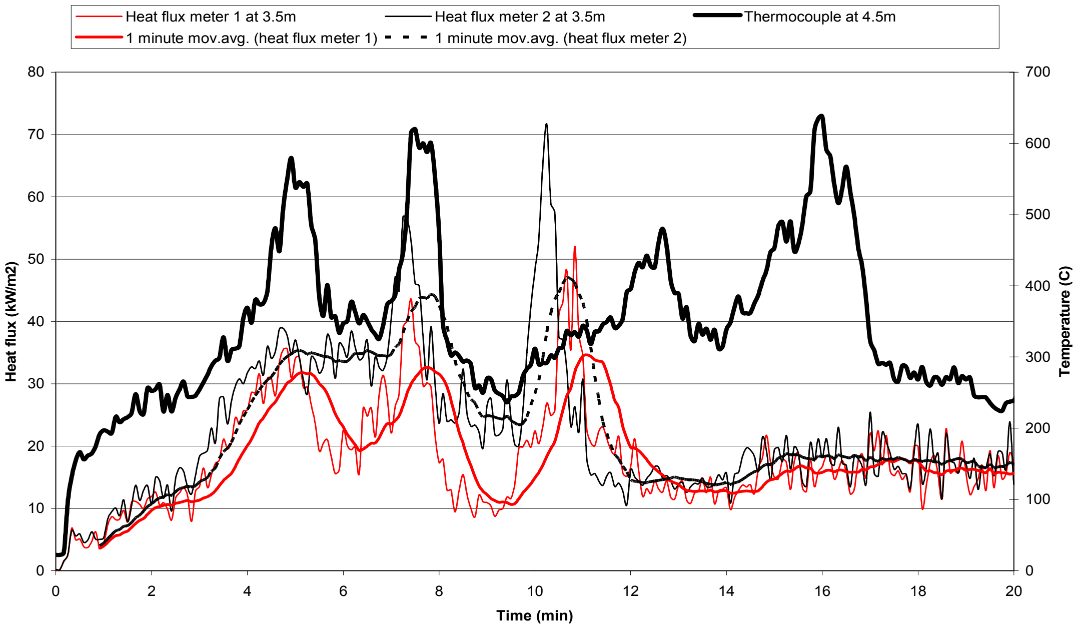

Figure 7-3: Plywood Test II heat flux at 3.5 m and temperature at 4.5 m (channel height 5000 mm).

7.4 Summary

The duration of Plywood Test I limits the comparison between the two plywood tests to just under eight minutes. It is of note that while there is clearly a difference in the heat flux recordings between the two tests after the first three minutes, the pattern of peaks and troughs appears consistent (refer Figure 7-4). The temperature data collected from the window opening thermocouple has been included to illustrate the consistency in the exposure conditions achieved between the two tests.

The critical dimensions for correlation with the full-scale test (ULC, 1992) are those used in the pass/fail assessment criteria. These are:

1. The location of the heat flux meters at 3.5 m, and

2. Flame spread exceeding 5 m.

Table 7-1: Times during which failure criteria have been exceeded for Plywood Tests I and II.

Test number	Failure criteria	
	Duration that the temperature at 4.5m > 500°C from (s) to (s)	Duration that the exposure recorded by either of two heat flux meters at 3.5m > 35 kW/m² from (s) to (s)
Test I	From 465 to 475* (test terminated after 475 s)	Not exceeded
Test II	From 280 to 315 From 435 to 475 From 935 to 995	From 260 to 300 From 335 to 390 From 415 to 470 From 585 to 635

* does not meet the duration criteria requiring the temperature to exceed 500°C for more than 30 seconds.

The two tests performed differently with Plywood Test I exceeding the flame spread criteria after 465 seconds, and Plywood Test II exceeding the heat flux criteria after 260 seconds and the flame spread criteria 20 seconds later after 280 seconds.

The difference in the times recorded for each test to first exceed the failure criteria is attributed to the plywood in Plywood Test I curling away from the channel wall, deflecting the flames away from the plywood in the upper channel. The deflection of the flames led to a reduction in the exposure conditions. After the curled section had burnt sufficiently to fall from the wall, normal exposure conditions resumed and the flame front accelerated rapidly up the channel resulting in the test being terminated early to prevent predicted building damage. Throughout both tests, the exposure conditions are very similar. A plot of the window opening temperatures for the two tests (refer Figure 7-4) demonstrates almost identical performance up to the end of Plywood Test I (i.e. for approximately the first eight minutes).

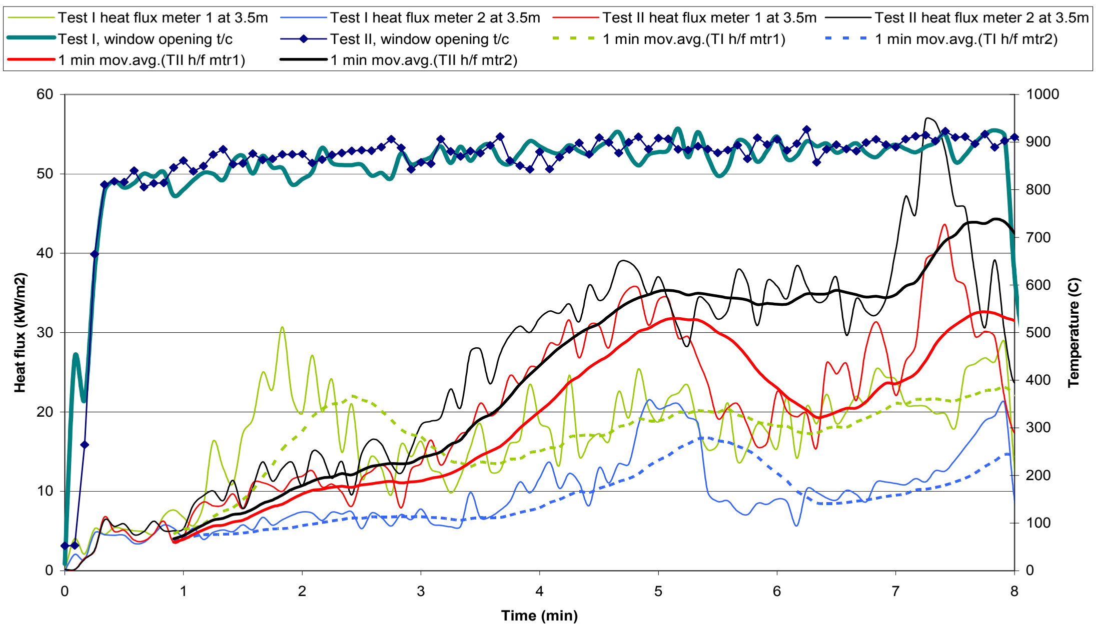

Figure 7-4: Heat flux measurements from Plywood Tests I and II

The important factor here was that the test results were consistent in determining that plywood is not suitable for use as a façade cladding intended to resist vertical fire spread. It has been demonstrated that the reduction in channel height has not led to a reduction in the severity of the test, and from that there can be confidence that a façade material would be tested adequately by the reduced height channel. Importantly the Vertical Channel Test maintains the correlation back to the original full-scale Canadian test method CAN/UL S134–92.

8. CONCLUSIONS/SUMMARY

The Vertical Channel Test has already been demonstrated by NRC to be a suitable fire test capable of testing the propensity for vertical flame spread on combustible cladding systems, albeit at a greatly reduced scale. The research presented in this report has built on the initial NRC development with a refinement of the test method and a further significant reduction in the overall height of the channel. The modifications extend to bringing the combustion chamber window openings in line with the proportion ratios used in the full-scale test.

A cost-effective pre-test screening method has been developed and is demonstrated to provide a more realistic prediction of full-scale test performance than that presently used in the BIA Acceptable Solutions. It is important to note that this assessment method has been developed particularly to address the overly severe method specified for the cone testing of materials where the outer metal skin has a melting point of less than 750°C, such as aluminium composite materials. It is not intended for this pre-screening method to be used as an alternative to full-scale testing or as a modification to the existing cone evaluation method for all other materials. It is considered that the existing Acceptable Solution for evaluation using the cone is reasonable for all materials, with the exception of those where it stipulates that the outer metal layer is removed prior to testing. In this instance, full-scale testing is recommended for regulatory assessment of performance. The pre-screening method developed and presented in this report is designed to assist in the product research and development phase as a more viable alternative to full-scale testing.

The Vertical Channel Test procedure as developed in this report has been documented in the format of a test procedure (refer BRANZ Technical Recommendation TR 16: *Proposed standard test method for surface flammability of combustible cladding and exterior wall assemblies using vertical channel apparatus*). This document details the geometry of the test equipment, the requirements for assembly and instrumentation of the test specimen, the test procedure and acceptance criteria.

9. RECOMMENDATION

It is the recommendation of this report that the Vertical Channel Test method (as documented in BRANZ Technical Recommendation TR 16: *Proposed standard test method for surface flammability of combustible cladding and exterior wall assemblies using vertical channel apparatus*) is included as an approved method of test for establishing compliance with the New Zealand Building Code Acceptable Solution C/AS1 Section 7.11.2 (BIA, 2001).

10. REFERENCES

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11. APPENDIX A

11.1 Test Rig Diagrams

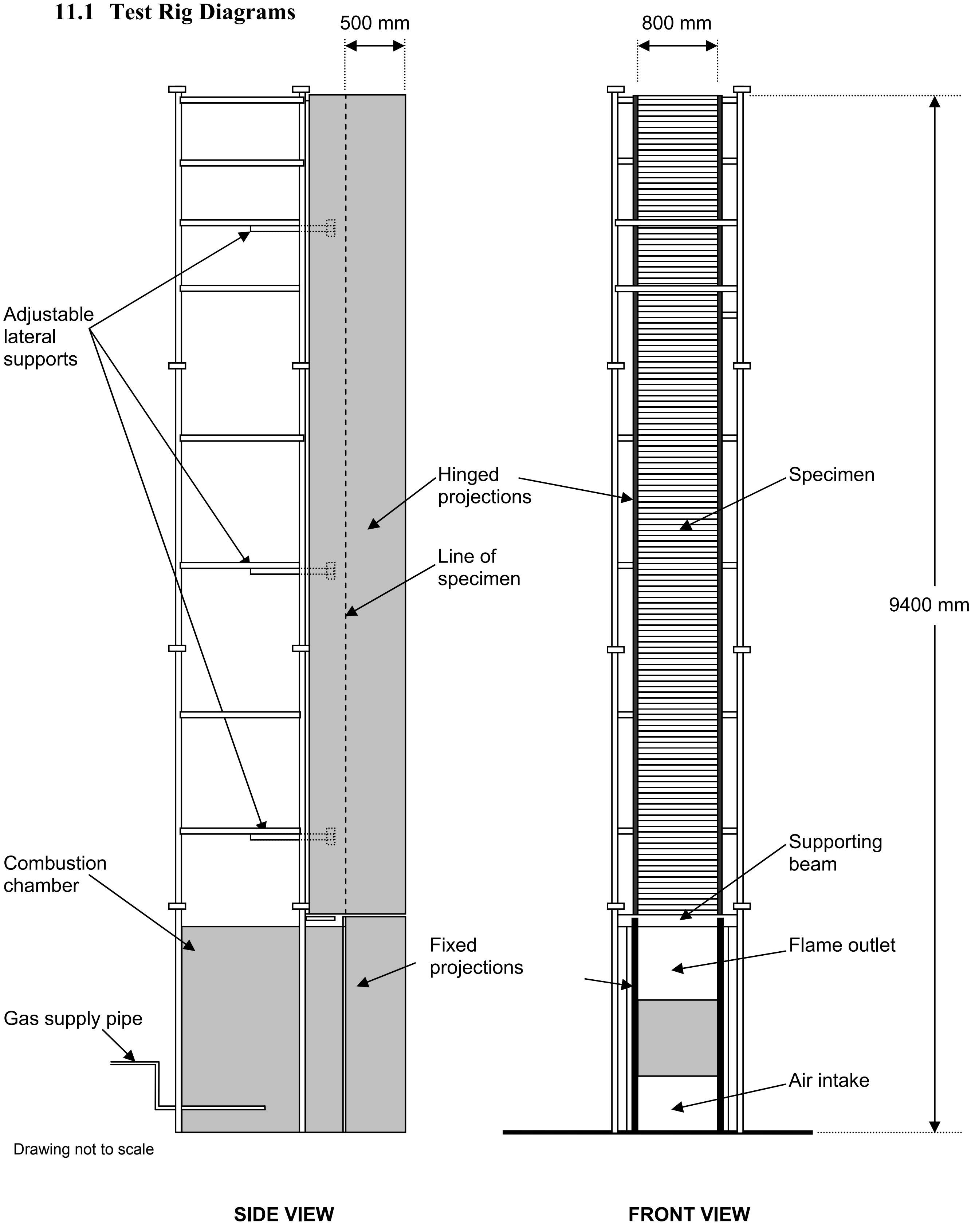


Figure 11-1: Test apparatus – original (ASTM, 1992)

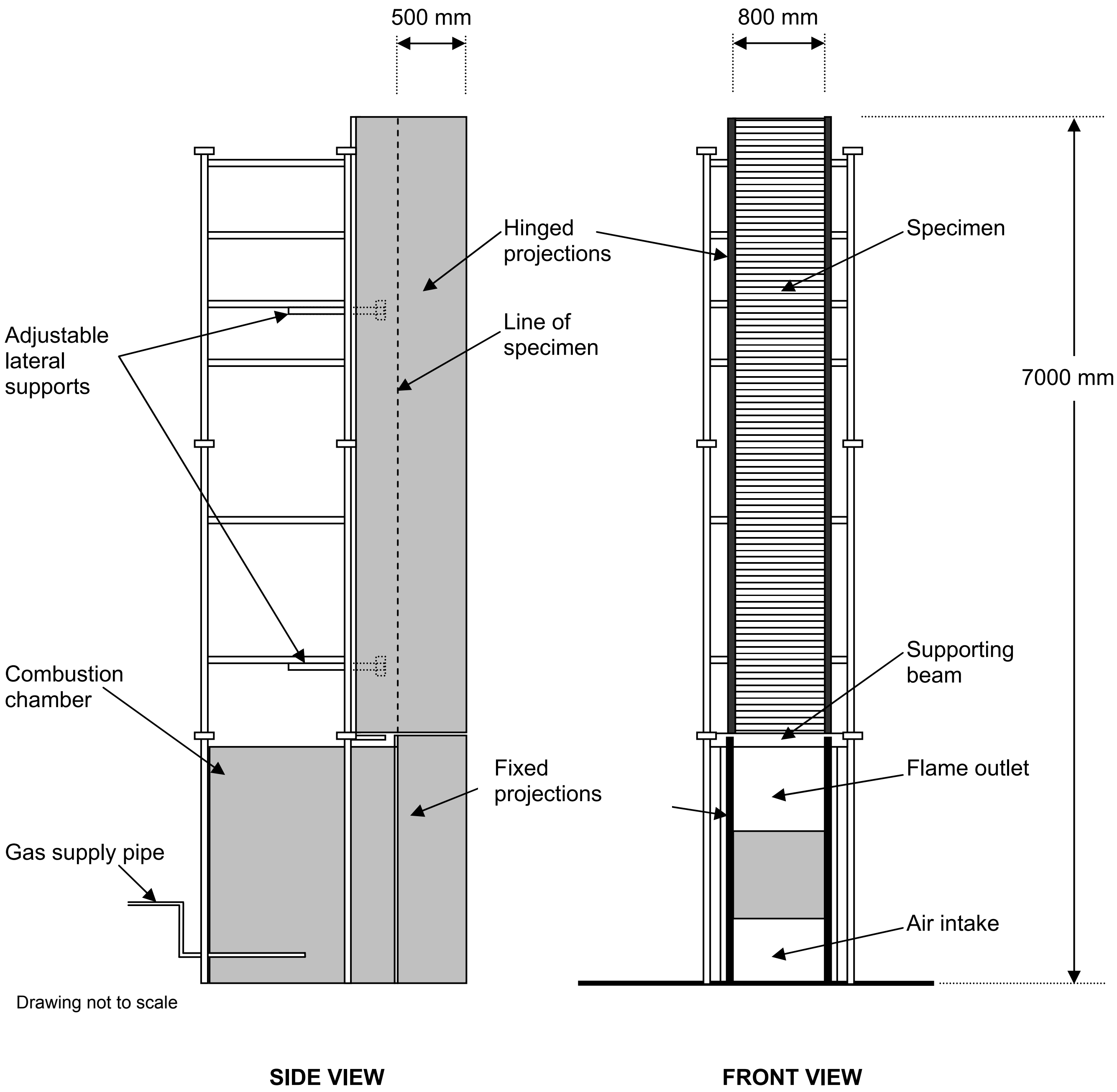
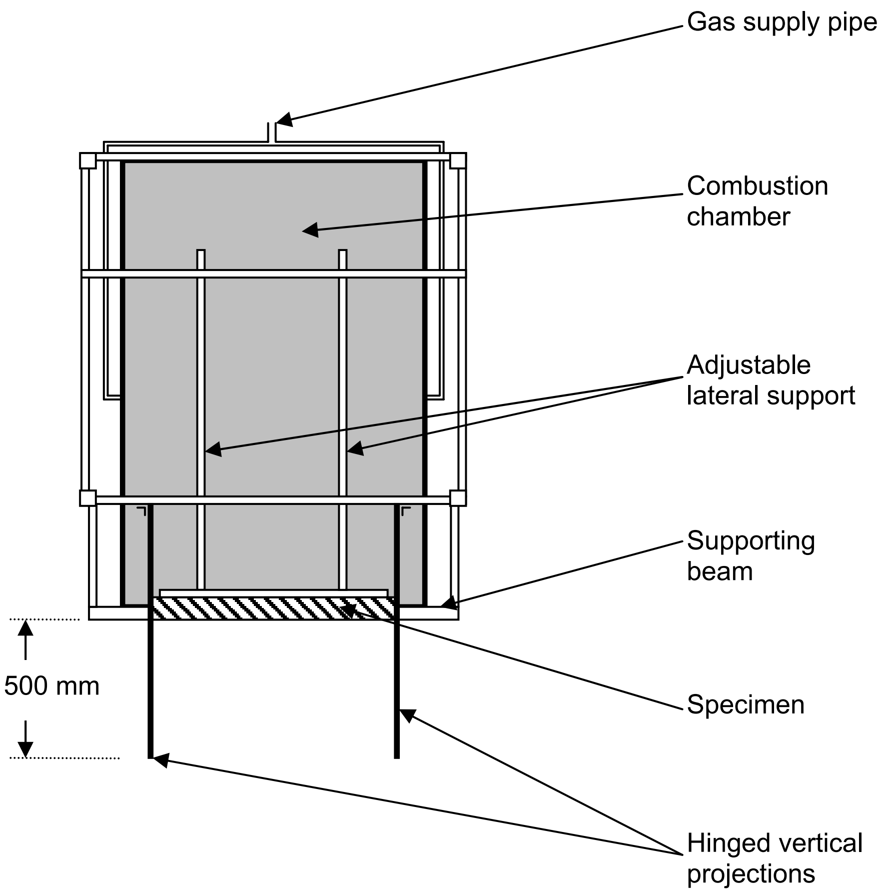


Figure 11-2: Test apparatus – proposed by BRANZ



Drawings not to scale

Figure 11-3: Horizontal cross-section above combustion chamber (ASTM, 1992)

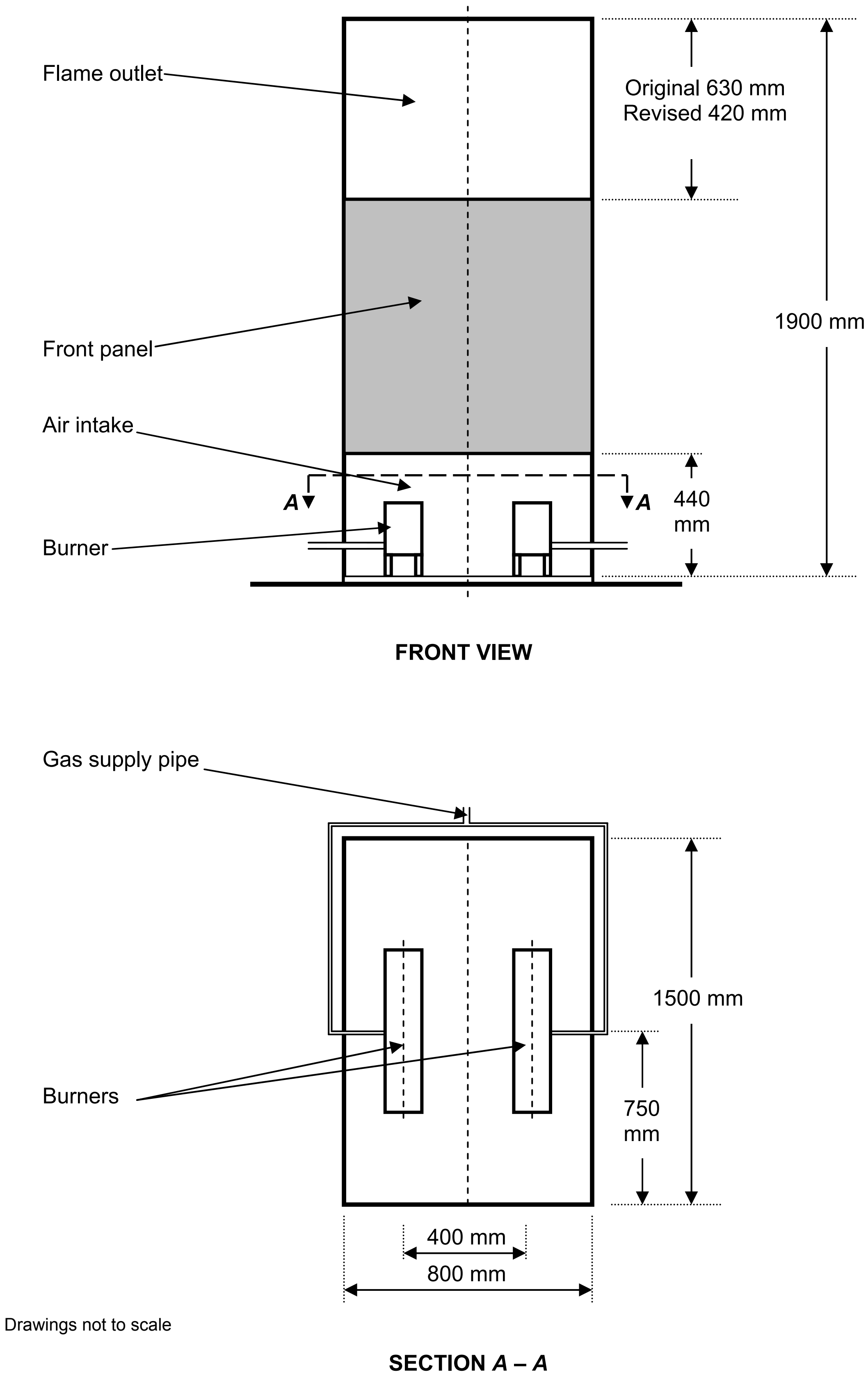


Figure 11-4: Combustion chamber details (original dimensions ASTM, 1992)

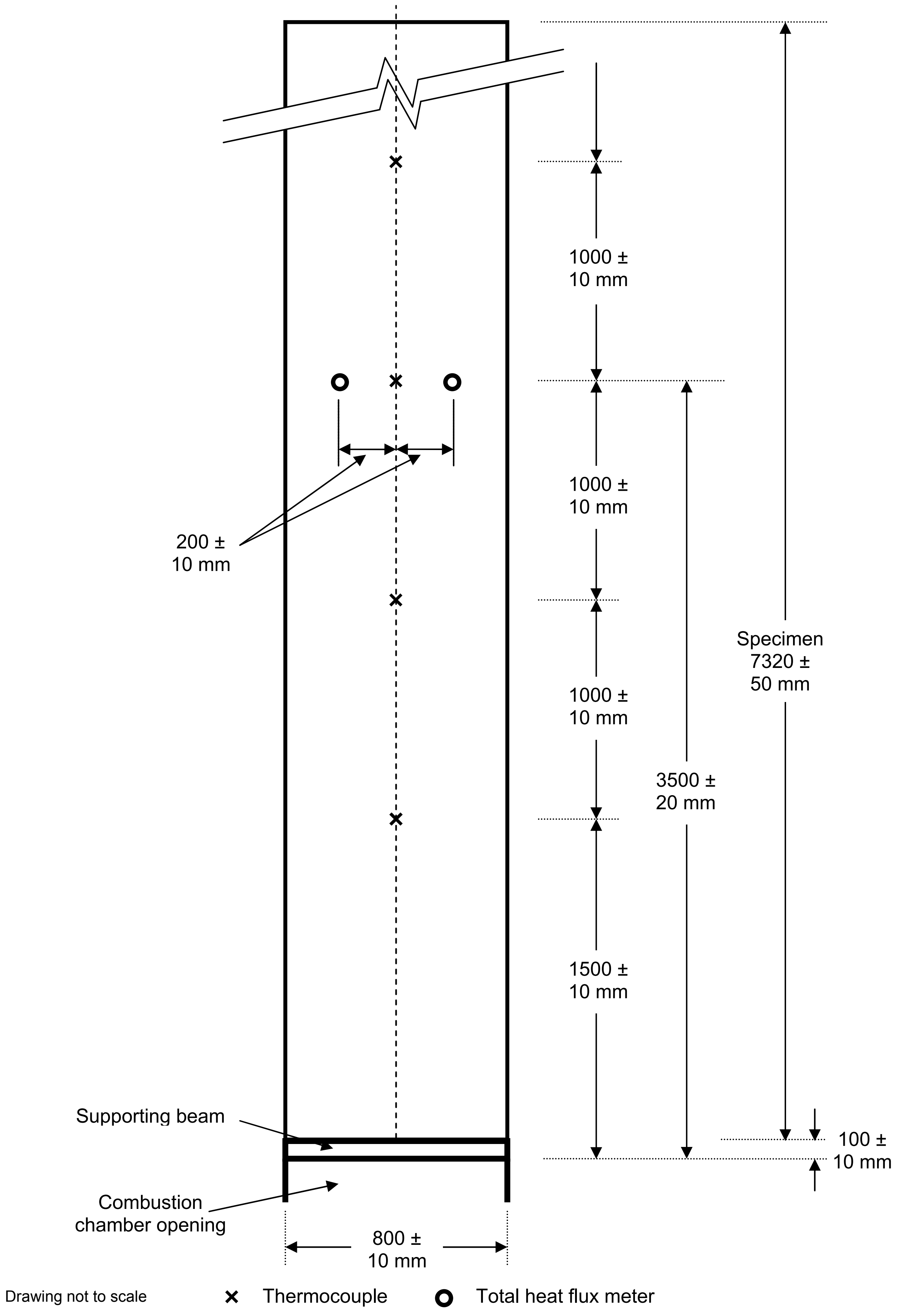


Figure 11-5: Specimen dimensions and instrumentation layout – original (ASTM, 1992)

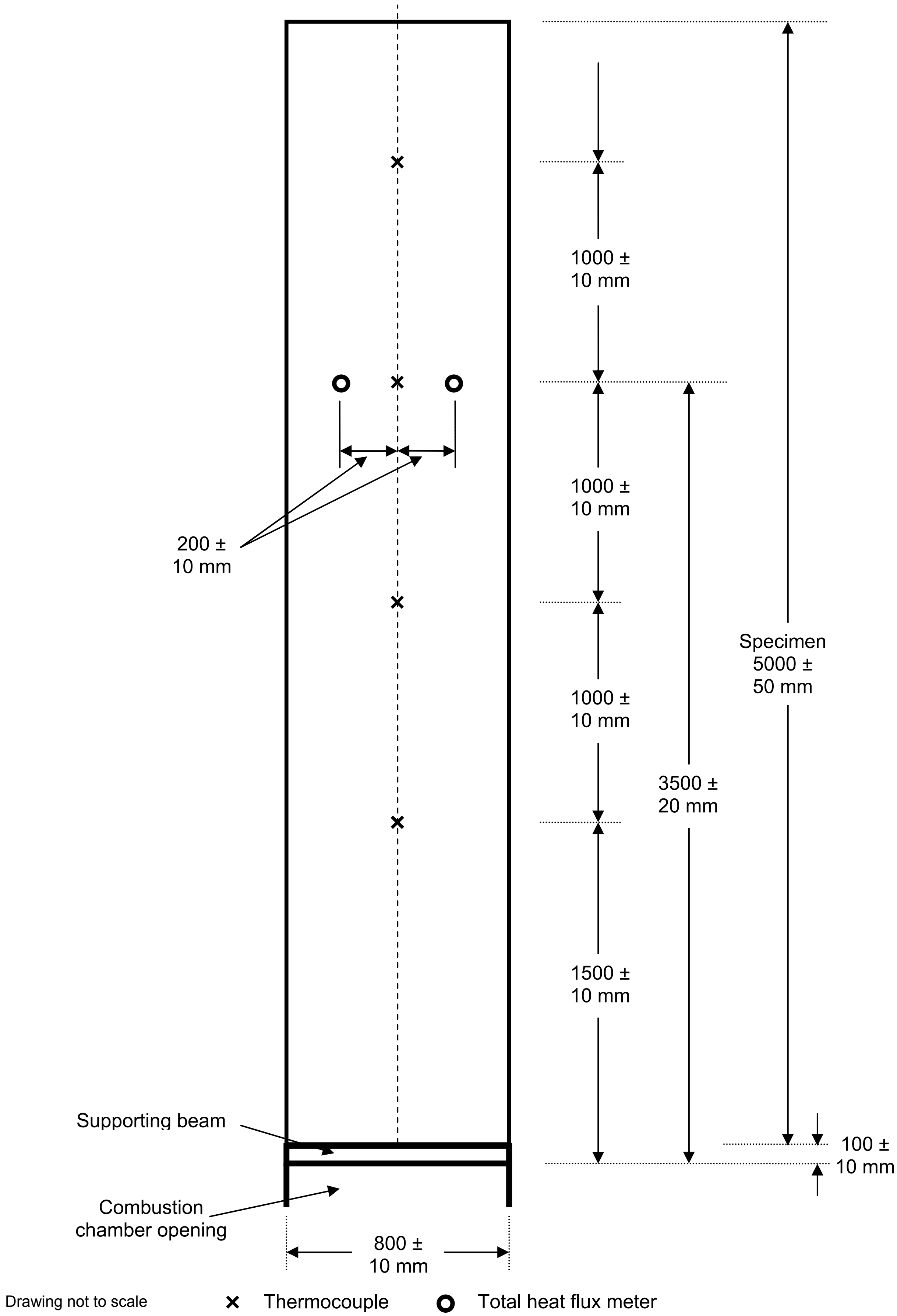


Figure 11-6: Specimen dimensions and instrumentation layout – proposed by BRANZ

12. APPENDIX B

12.1 Heat Flux Plate Calculation method

The Heat Flux Plate Calculation method is based on NIST publication NIST–GCR–98–756 (http://fire.nist.gov/bfrlpubs/fire98/art058.html).

The total heat flux to any location on the steel plate has been determined from taking the following combination of heat transfer effects into account:

- heat loss to the ceramic fibre insulation
- reduction in heat flux due to high temperature of the plate
- correction to equate with the cold surface of water cooled heat flux meters.

The incident heat flux $\dot{q}''_{i,meas}$ can be calculated from the temperature measurements by:

$$\dot{q}''_{i,meas} = \rho c \delta \frac{dT}{dt} + \varepsilon\sigma\left(T_s^4 - T_\infty^4\right) + \dot{q}''_k$$

Where

$\rho c \delta \frac{dT}{dt}$ is the energy storage within the steel

Here the specific heat (c) is temperature dependent:

$c = 0.0007T^2 - 0.0058T + 486$ J/kg K where 0°C < T < 700°C

$c = 11.72\ (T - 700) + 846$ J/kg K where 700°C < T < 750°C

$c = -\ 9.64\ (T - 750) + 1432$ J/kg K where 750°C < T < 850°C

$\varepsilon\sigma\left(T_s^4 - T_\infty^4\right)$ is the net re-radiation losses with respect to the environment (temperature in K)

$\dot{q}''_k$ is the conduction heat losses through the steel (in the x and y directions), and is approximated by:

$$\dot{q}''_k \approx -k_{st}\left(\frac{T_{x+\Delta,y} + T_{x-\Delta,y} + T_{x,y+\Delta} + T_{x,y-\Delta} - 4 \cdot T_{x,y}}{\Delta^2}\right)\delta$$

where

$$k_{st} = -3\times10^{-5}\cdot T^2 - 0.0115\cdot T + 51.9$$

Including the conduction losses to the ceramic fibre insulation and the cold surface correction factor, results in the following expression for the total incident heat flux from the plume onto a cold surface.

$$\left(\dot{q}''_{i,pl}\right)_{cold} = \rho c \delta \frac{dT}{dt} + \varepsilon\sigma\left(T_s^4 - T_\infty^4\right) + \dot{q}''_k + \dot{q}''_{k,ins} + h_c\left(T_s - T_0\right)$$

Where

$\dot{q}''_{k,ins}$ is the conduction losses to the ceramic fibre insulation. In experimentation this was found to average 5.1 % of the incident heat flux. Therefore adding this correction gives:

$$\dot{q}''_{i,ins} = 0.05\left(\dot{q}''_{i,meas}\right)$$

and

$h_c\left(T_s - T_0\right)$ is the cold surface correction factor.

A cold surface correction factor is introduced to account for the increasing temperature of the steel plate causing the convection portion of the heat flux from the plume to decrease resulting in a slight reduction in the measured heat flux. The correction factor is necessary to equate the steel plate measurement to that measured by a water cooled heat flux meter.

The cold surface correction factor is calculated from:

$$h_c = \frac{N_u \cdot k_a}{l}$$

where

$$N_u = \left[0.825 + \frac{0.387 \cdot R_a^{1/6}}{\left[1 + \left(0.492/P_r\right)^{9/16}\right]^{8/27}}\right]^2$$

$$R_a = G_r \cdot P_r$$

$$G_r = \frac{g\beta\left(T_s - T_\infty\right)l^3}{v^3}$$

$$\beta = \frac{2}{T_s + T_\infty}$$

$$P_r = \frac{v}{a}$$

$$k_a = -3\times10^{-8}\cdot T^2 + 7.76\times10^{-5}\cdot T + 0.024281 \qquad \text{W/m K}$$

$$a = 7\times10^{-11}\cdot T^2 + 1.562\times10^{-7}\cdot T + 1.8176\times10^{-5} \qquad \text{m}^2\text{/s}$$

$$v = 7\times10^{-5}\cdot T^2 + 0.0974\cdot T + 13.159 \qquad \text{m}^2\text{/s}$$

The thermal diffusion time in seconds for the steel plate is calculated from:

$$t = \frac{\delta^2 \rho c}{k_{st}} \qquad \text{(s)}$$

Nomenclature

ρ	density (steel = 7860)	(kg/m^3)
c	specific heat	(J/kg K)
δ	steel plate thickness	(m)
ε	emissivity	
T	temperature	(°C) except where noted
T_s	steel surface temperature	(°C)
T_0	initial steel surface temperature	(°C)
T_∞	ambient temperature	(°C)
t	time	(s)
l	height (length) of plate	(m)
h_c	convection heat transfer coefficient	(W/m^2 K)
N_u	Nusselt number	
P_r	Prandtl number	
a	thermal diffusivity	(m^2/s)
$\dot{q}''$	heat release rate	(kW/m^2)
Δ	distance between thermocouple nodes	(m)
G_r	Grashof number	
g	acceleration due to gravity (9.807)	(m/s^2)
β	volumetric thermal expansion	(1/K)
v	kinematic fluid viscosity	(m^2/s)
σ	Stefan-Boltzmann constant (5.670×10^{-11})	(kW/m^2 K^4)
k_{st}	thermal conductivity of the steel	(W/m K)

13. APPENDIX C

13.1 BRANZfire input data

```
Input Filename : C:\Program Files\BRANZFIRE2003\data\VCT- wall ACM 6.mod

BRANZFIRE Multi-Compartment Fire Model (Ver 2003.1)

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====================================================================
Description of Rooms
====================================================================
Room  1  : Wall of VCT
         Room Length (m) =                                20.00
         Room Width (m) =                                 20.00
         Maximum Room Height (m) =                        10.00
         Minimum Room Height (m) =                        10.00
         Floor Elevation (m) =                            0.000
         Room  1  has a flat ceiling.

         Wall Surface is ACM Type F
         Wall Density (kg/m3) =                           1700.0
         Wall Conductivity (W/m.K) =                      0.030
         Wall Emissivity =                                0.88
         Wall Thickness (mm) =                            3.5

         Wall Substrate is calcium silicate
         Wall Substrate Density (kg/m3) =                 720.0
         Wall Substrate Conductivity (W/m.K) =            0.120
         Wall Substrate Thickness (mm) =                  20.0

         Ceiling Surface is calcium silicate
         Ceiling Density (kg/m3) =                        720.0
         Ceiling Conductivity (W/m.K) =                   0.120
         Ceiling Emissivity =                             0.83
         Ceiling Thickness (mm) =                         20.0

         Floor Surface is concrete
         Floor Density (kg/m3) =                          2300.0
         Floor Conductivity (W/m.K) =                     1.200
         Floor Emissivity =                               0.50
         Floor Thickness = (mm)                           100.0

====================================================================
Description of Wall Vents
====================================================================
From room  1  to outside, Vent No 1
                   Vent Width (m) =                       20.000
                   Vent Height (m) =                      10.000
                   Vent Sill Height (m) =                 0.000
                   Vent Soffit Height (m) =               10.000
                   Opening Time (sec) =                   0
                   Closing Time (sec) =                   1200

====================================================================
Description of Ceiling/Floor Vents
====================================================================
====================================================================
Ambient Conditions
====================================================================
Interior Temp (C) =                                       15.0
Exterior Temp (C) =                                       15.0
Relative Humidity (%) =                                   65

====================================================================
Tenability Parameters
====================================================================
Monitoring Height for Visibility and FED (m) =            2.00
Occupant Activity Level =                                 Light
Visibility calculations assume:                           reflective signs
```

```
FED Start Time (sec)                                        0
FED End Time (sec)                                          600

====================================================================
Sprinkler / Detector Parameters
====================================================================
No thermal detector or sprinkler installed
====================================================================
Mechanical Ventilation (to/from outside)
====================================================================
Mechanical Ventilation not installed in Room 1

====================================================================
Description of the Fire
====================================================================
Radiant Loss Fraction =                                     0.29
Soot Alpha Coefficient =                                    2.50
Smoke Epsilon Coefficient =                                 1.20
Smoke Emission Coefficient (1/m) =                          13.32
Characteristic Mass Loss per Unit Area (kg/s.m2) =          0.011
Air Entrainment in Plume uses McCaffrey (default)

Burning Object No 1

              Located in Room                               1
              Energy Yield (kJ/g) =                         43.7
              CO2 Yield (kg/kg fuel) =                      2.340
              Soot Yield (kg/kg fuel) =                     0.024
              Fire Height (m) =                             0.300
              Fire Location (m) =                           Wall

              Time (sec)               Heat Release (kW)
               0                       0
               5                       50
               1200                    50

====================================================================
Post-flashover Inputs
====================================================================
Post-flashover Model is OFF

====================================================================
Flame Spread Inputs
====================================================================
This simulation includes flame spread on linings.
Cone Calorimeter Ignition data is correlated using the Flux Time Product method.
Quintiere's Room Corner model is used.
Flame Length Power =                                        1.000
Flame Area Constant =                                       0.0083
Burner Width (m) =                                          0.800

Room 1
Wall Lining
              Cone HRR data file used =                     ACM Type F.txt
              Heat of combustion (kJ/g) =                   19.4
              Soot/smoke yield (g/g)=                       0.000
              Min surface temp for spread (C) =             0.0
              Flame spread parameter =                      0.0
              Ignition temperature (C) =                    352.7
              Thermal inertia =                             0.766
              Critical Flux for Ignition (kW/m2)            13.4
              Ignition Correlation Power
              (1=thermally thin; 0.5=thermally thick)       1.00
              Flux Time Product                             2006

====================================================================
```

14. APPENDIX D

14.1 Vertical Channel Test – Plywood Test I Observations

Elapsed time min:sec	Observations
0:40	Flames attached to lower 200 to 300 mm of plywood sheet one*, with charring over the lower half of sheet one (0 to +2400 mm). Flame height approximately 1000 mm
1:30	Flame spread to +1000 mm, flame extensions exceed 2000 mm
2:00	Char front reaches plywood sheet two** (+2400 mm), considerable turbulence in the flaming at base of plywood sheet one. Bottom edge of plywood sheet one begins to curl away from channel wall
3:00	Flame extensions exceed 2500 mm
3:30	Flame extensions exceed 3000 mm
4:00	Flames spread to plywood sheet two (+2400 mm). Flames spread beyond the heat flux meters (+3500 mm) with flame extensions exceeding 4000 mm
5:00	The bottom 800 mm of plywood sheet one falls to the floor with flame spread beyond 3600 mm
5:10	The remaining ply in sheet one begins to curl away from the wall along the bottom edge. Flame density on the wall above 800 mm reduces significantly over the next 15 seconds
5:30	Flames are attached at several locations including the bottom edge of plywood sheet two (+2400 mm). Flame extensions do not exceed 3000 mm
6:00	The bottom 1000 mm of plywood has burnt away
6:30	The bottom 1200 mm of plywood has burnt away. Flame extensions exceed 4000 mm
7:00	The bottom 1500 mm of plywood has burnt away. Flame extensions exceed 5000 mm
7:30	The bottom 1800 mm of plywood has burnt away. Flame extensions exceed 6000 mm
7:40	The bottom 2000 mm of plywood has burnt away. Flame extensions exceed 7000 mm. Flames attached to plywood up to 4500 mm
7:50	Flame extensions beyond the top of the channel (exceed 7320 mm). Flames attached to plywood up to 5000 mm Test terminated

*Plywood sheet one measures from 0 to 2400 mm
**Plywood sheet two measures from 2400 to 4800 mm

14.2 Vertical Channel Test – Plywood Test II Observations

Elapsed time min:sec	Observations
0:40	Flames attached to lower 200 to 300 mm of plywood sheet one, flame height approx 1 m
1:30	Flame extensions exceed 2000 mm. Considerable turbulence in the flames at the base of plywood sheet one
2:30	Flame extensions exceed 3000 mm
3:00	Flames attached to plywood to height of 1500 mm
3:30	Flame extensions exceed the heat flux meters at 3500 mm reaching almost to 4000 mm
4:00	Flame extensions exceeds 5000 mm
4:50	The bottom 800 mm of plywood sheet one falls from the channel. Flame density on the wall above 800 mm reduces significantly over the next 15 seconds with flame extensions not exceeding 3000 mm
5:30	The bottom 1000 mm of plywood has burnt away. Flame extensions exceed 6000 mm
6:00	The bottom 1000 mm of plywood is burnt away
7:30	Almost all of plywood sheet one consumed and fallen from the channel
9:15	Burning observed under the lower edge of plywood sheet two (+2400 mm)
9:30	Flame tips exceed 5000 mm
11:30	Flame front reached approximately 4000 mm
13:00	Flame intensity subsides
14:00	Trailing edge of flame front at approximately 4200 mm
16:00	Trailing edge of flame front at approximately 4500 mm
19:00	Trailing edge of flame front at approximately 4800 mm
20:00	Test terminated