School of Engineering

University of Southern Queensland

Testing non-metallic ember proof screens for dwellings within bushfire attack regions

Daniel Bellert (BENH Mechanical)

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Declaration

I certify that the information, experimental work, results and reporting found herein is entirely my own, excepting where appropriate referencing acknowledges otherwise.

The contents are original and have not been submitted at any other institution nor for any other certification.

Daniel Bellert

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Abstract

Bushfire embers, as created by the burning plant litter can be swept high into the air and travel many kilometers whilst remaining alight, potentially igniting flammable materials wherever they land. Certain regions of built up areas are considered at risk of ember attack and must have protection against the floating embers built in. After prolific and devastating Australian bushfires in 2009, AS3959 was created which mandates dwellings within these bushfire prone areas must have metallic screens fitted over windows. The regions have been allocated by the potential radiation levels they might endure during a bushfire. As materials science advances it allows for implementation of better performing and more versatile screen materials. The main aim of this research and testing is to ascertain the suitability of non-metallic, flexible, polymer based materials which can be implemented as screens against ember attack, allowing more cost effective, flexible, and widespread installation of ember screens in dwellings.

In previous testing predominantly conducted in Japan and USA, the main focus of the testing has been on steel and aluminium screens with little attention paid to other options. While metallic screens may be the most obvious solution to stopping ember attack, they have limitations. Metallic screens can be expensive to manufacture and install and they have limited installation options due to their rigid form. New options have emerged in the form of a fire-proof foam and many types of fireproofing sprays, designed for application to synthetic materials.

Testing was conducted using the Ember Shower Simulator (ESS). The ESS was be used to simulate high wind speed conditions of a real bushfire by propelling burning embers at the test materials. The testing was recorded using high frame rate video recording for later analysis. Testing materials are a) Fire-proof foam, b) Shade cloth with fire-proofing spray applied, c) PVC Canvas exterior roller blind material with fire-proofing spray applied.

The testing, conducted over several sessions, has shown the high performance of the fire-proof foam, along with mixed results for the support materials. While the results from the testing are encouraging, they don’t allow for any direct application of the tested materials into the fire-proofing market, Rather, the results from this testing open the materials to more rigorous and extensive future testing.

Contents

Introduction

Bushfires are a natural part of many ecosystems around the world. The serve the purpose of clearing forested areas of dry, dead litter and underbrush which has accumulated naturally over time. The problem arises as human infrastructure spreads wider each year and starts to encroach on natural wooded areas which have largely remained untouched. These areas where the human built environment approaches natural, untouched forested areas are referred to as Wildland Urban Interfaces (WUI) and the problem occurs with the ignition of a natural bushfire near this region. When this happens the structures and dwellings within the WUI become subject to the destructive aspects of the fire. Studies from around the world have shown that the embers generated in WUI bushfires can travel many kilometers on the wind while remaining alight, and when they land in and around dwellings they will ignite new bushfire fronts. This can have catastrophic consequences such as creating bushfire fronts which completely block evacuation roads and large scale destruction of property as burning embers float into on around people's houses, thereby setting their house alight. Many governments have instigated rules and standards which require houses within a certain distance of potential bushfire regions to install protective screens on their doors and windows. The Australian government created Australian Standard 3959 in 2009 after more than 2000 dwellings were lost in one of the most severe bushfire events in recent memory. This standard stipulates, among other things, installation of specific metallic screens over doors and windows of houses within the WUI, in known bushfire regions country wide. While this regulation has been tested as effective against the ingress of burning embers into dwellings, the screens are restrictive and expensive to manufacture and install, and there also remains many other ignitable sources around the dwellings which remain unprotected by the screens.

This project aims to investigate, via the use of a specifically designed testing apparatus, other potential methods of protecting dwellings from an ember attack. The apparatus to be used is the Ember Shower Simulator (ESS), located at the University of Queensland Toowoomba campus. It generates a continuous stream of embers which can be directed against any object or test material, thereby assessing the suitability of that object or material to withstand ember attack.

During the course of this project, materials and or designs which are currently not in place will be considered and tested for suitability. The aim is to find a solution which is inexpensive, readily available and manufactured and which can protect more than just the windows and doors of an at risk dwelling. To do this, a complete review of the current testing being undertaken at various reputable scientific institutions around the world will be assessed to find if there is any opportunities for new designs and materials which are currently not being researched. Once these opportunities are identified, a set of tests will be implemented using the ESS which will give information about the suitability of new materials or designs.

2 – Literature Review

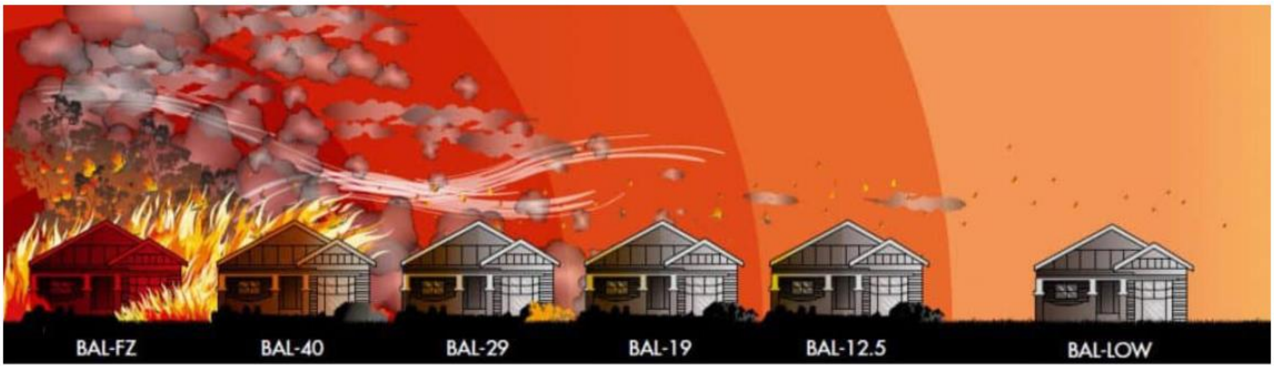
Given the potentially high toll exacted by some bushfires, both in human and economical terms, it is not surprising that there is a substantial body of research into the science behind them. This research is carried out at several reputable institutions throughout the world and ranges from the cause of bushfires and urban fires, to preventative methods employed by many international governments and institutions.

As this project is being completed using the Ember Shower Simulator (ESS) designed and constructed at USQ the focus of the literature research remained on firebrands rather than the bushfires themselves.

In reviewing the research, it was quickly evident that previous researchers had focussed on many of the same aspects of firebrand analysis, such as firebrand size, behaviour and ability to ignite a flammable fuel, and more importantly the use of screens to contain or control the firebrands.

2.1 – Bushfire Attack Levels (BAL):

The developed region used for new housing estates, within a certain minimal distance of bushland is referred to as the wildland-urban interface (WUI). Housing at certain distances from the bushland is rated in BAL regions. These regions are particular to the local area and depend on localised factors such as geography, terrain, and flora. Bushfire screens are rated by what BAL level they are designed to resist. The BAL levels are as such:



(https://www.takt.net.au/bushfire-attack-levels)

BAL LEVEL OVERVIEW

BAL LOW – Very low risk. There is insufficient risk to warrant specific construction requirements.

BAL 12.5 – Low risk. Ember attack with heat flux up to 12.5kW/m^2. Some construction requirements relating to the external surfaces of the building.

BAL 19 – Moderate risk. Increasing levels of ember attack, burning debris ignited by windborne embers. Heat flux up to 19kW/m^2. Construction requirements relating to external materials, glazing and detailing.

BAL 29 - High risk. Increasing levels of ember attack and burning debris from windborne embers. Increasing heat flux up to $29kW/m^2$. Construction requirements relating to external materials, glazing detailing and additionally to subfloors and floor construction.

BAL 40 – Very high risk. Increasing levels of ember attack and burning debris with increasing heat flux up to $40kW/m^2$ and increasing likelihood of exposure to flames. Significant construction requirements for all parts of the building.

BAL FZ – Extreme risk. Direct exposure to flames from fire, in addition to heat flux greater than $40kW/m^2$ and ember attack. Significant protection is required to reduce the threat, such as radiant heat barriers and modifications to the building and surrounding property. Significant construction requirements for all parts of the building and specific requirements to protect all openings.

2.2 – Testing Screen Types

One of the main purposes of the ESS is to assess the effectiveness of various firebrand blocking screens. Most of the research available would source locally available screens which were rated to the Australian Standard 3959 2018 and subject these to various firebrand shower conditions. It was found that the main focus of most studies was not in fact the testing many types of screens but rather the testing of a few types of screens in many and varied conditions. A review of commercially available fire mesh screens in Australia has shown that most companies will offer between one and three types of screen, usually stainless steel screens with two or three different aperture sizes and a cheaper aluminium option for customer in a lower BAL rated region.

2.2.1 – Screen Geometry

There was little to no research done on screens with different geometries. All screens tested were of the flat, woven wire design. One study [5] showed the benefit of placing two screens in place together, and further investigated the effect of changing the distance between them. As yet however, there is no evidence that other screens with varying overall shapes, such as an accordion or waves, have been tested. Further study here could investigate the effectiveness of easily mass produced stamped style hinged or even perforated screens with varying stamped shapes and 3D profiles.

2.2.2 – Screen performance at different firebrand incident angles:

There is limited research done into how screens perform when comparing the way in which the firebrand impacts the screen. A study [8] conducted by the National Institute of Standards & Technology in the US (NIST) in collaboration with the Building Research Institute in Japan (BRI) use the NIST dragon ember shower generator, which with its vertical spout design created unpredictable and non-uniform showers of firebrands. This study however, was designed to observe and analyse the effects of firebrands on a whole building, rather than specifically on a screen. Most studies appear to use a straight wind tunnel with no adjustable vanes for directing the flow of the wind laden with firebrands. One study examined this by placing the screen at different angles, but as yet there has been no study found which uses anything but airflow down a straight, uninhibited wind tunnel. A further area of study here may be to build an apparatus with adjustable vanes inside the wind tunnel.

These vanes could be used to incite different flows in the wind, thereby allowing the firebrands to impact the screens at different angles. This may more accurately simulate real world conditions where winds are often forced into whirls and eddies due to the objects they flow around.

2.2.3 – Screen materials:

In all the testing reports found to date there is very little to no work done in investigating screens made from different materials. With materials science research advancing at an exponential rate, it is worth investigating if materials other than stainless steel and aluminium can be used for AS3959 rated screens. A future area of research here might be to investigate fireproof polymer screens, which would be cheaper to produce and have a more versatile range of applications.

2.3 – Testing Alternatives to Metal Screens

It's understandable that most of the testing and research done so far would be on testing wire mesh screens, as these are not only prescribed in AS3959 but also imitate the very commonly used and accepted PVC coated fibre glass fly screens, found in most modern dwellings. This however leaves a large gap in the current research where there is no investigation into alternatives to wire mesh screens. The only alternatives found were from retailers, and based on a louvre system. A macroscopic louvre system (breezeway.com.au) was tested by the CSIRO for fireproof and firebrand proofness, but it was still marketed as a multi-phase product; louvres in tandem with wire mesh, meaning the main defence against firebrand was still the mesh. A secondary and arguably better system was a micro-louvre setup which was not only certified to AS3959 standard, but also the more strict AS1530 standard, which allows for vegetation to be within 10m of the dwelling. It should be considered that future studies could include testing of curtains, better louvre designs, accordion screens and more materials for retractable screens.

2.3.1 – Different Apparatuses Available

There are currently studies into firebrand effect mitigation being carried out on many simulation apparatuses in many countries around the world. The Fire Research Wind Tunnel Facility (FRWTR) at the BRI in Japan is the largest fire research wind tunnel in the world, allowing for analysis of firebrand propagation on a large scale. The BRI and NIST have formed a fruitful partnership to further test screen resistance to firebrand attack. Other studies have been carried out on smaller apparatuses, with one study [9] using a portable firebrand generator which can be moved and used under different conditions in different environments.

A device created by NIST, called the Emberometer is designed to monitor and map the trajectories of firebrands so that better understanding might lead to better shielding. The Emberometer is a set of cameras mounted on a frame. The cameras observe the firebrands from four different viewpoints which allows for computer generated mapping of the firebrands.

Smaller apparatuses such as the ESS [2] and portable design [9] are capable of directing different conditions against test screens. These conditions might include faster wind speeds or more focused attention on the selected fuel type, screen orientation and localised environmental conditions in the wind tunnel.

2.4 – Testing Different Fuel Sources and Conditions

2.4.1 – Fuel Sources:

Most testing using wind tunnel devices to test firebrand behaviour and screen effectiveness has been done with limited consideration to the fuel source used. One test [2] used two types of fuel source for testing and found differences in the behaviour of the firebrand produced, but most of the testing done to date appears to use only a single fuel source. Even in [2], the fuel sources were doused with kerosene as an aid to ignition, which could affect the test results as most firebrands created by a bushfire would not come from kerosene doused fuel.

There was some effort to use the correct species of plant, but the fuel sources used were largely commercially available wood chips. A study by Sharifian [4] was completed using leaves as the fuel source and showed a correlation between the fragmentation ratio of the leaf firebrands and the diameter of the wire in the mesh.

Future studies could be done using a more accurately blended and size fuel source. Rather than using wood chips which are chipped pieces of the tree trunk and large branches, the fuel could be sourced from actual bushland foliage debris, namely sticks, pieces of bark, green and dried leaves. An amalgamation of what is actually being burnt during most bushfires. Further study could also focus on the species that are common and abundant in each area in order to provide a more specialised recommendation on firebrand proofing dwellings in that region.

2.4.2 – Conditions:

There are many studies which show the conditions under which bushfires start and spread quickly. Some of the firebrand studies have made note of the ambient environmental conditions but have made no effort to recreate typical bushfire conducive environment conditions in the testing facility. Even for the studies carried out during the hot, dry summer conditions that bushfires often thrive in, the studies are still carried out inside a controlled, lab environment. Future studies could incorporate testing under more accurate weather conditions, which will hopefully provide a more accurate set of results.

2.5 – Firebrand Behaviour

All previous studies have been setup with water pans to capture and extinguish live firebrands so that they can be analysed for mass and size however there have been several studies which analyse the specific behaviours of the firebrands.

A recent study [2] assessed the effectiveness of burning embers after passing through a screen. The study used high frame rate photography to analyse the firebrands which passed through the screen. The firebrands were then analysed further by their effect on a thin plastic membrane. The study showed typically eight behavioural patterns followed by firebrands created by two different fuel sources, which allowed for further comment on the effectiveness of ember screens. Another study [6] conducted at Florida State University used computational fluid dynamic modelling (CFD) to simulate the dispersion of firebrands around simulated urban structures. Modelling different firebrand sizes, the study showed how dwellings within certain BAL attack levels would experience firebrand attack.

Using a much larger simulator, the BRI in Japan is able to test not only firebrand size and effects on dwellings but also how the aerodynamic flows differ around larger structures.

Potentially, future studies in firebrand behaviour could focus on the possible combinations of fuel source which may exist in a real fire situation.

2.6 – Summary of Available Literature

As it stands there are rapidly advancing studies being carried out into ways to mitigate the effect of firebrands created during large fire events. Most studies are completed using firebrand shower simulators which allow for the testing of ember screens on dwellings nearby. The ember shower simulators are well designed and allow for various testing scenarios, however one area with little to no information was testing ember behaviour in highly turbulent, erratic wind flows and vortices. It is suggested that this may be an area for further study.

Ember behaviour has also been extensively studied with several reports giving detailed accounts of firebrand behaviour on a large and small scale. The only possible shortcoming of these studies is the choice of fuel used to create the firebrands. Further study here would use more thoroughly considered fuel types and mixes to accurately simulate real world conditions. This would also involve testing different fuel sources in different ambient conditions.

Despite the large quantity of research done on firebrand behaviour there appears to be little study done on possible materials which could be used for screens. Additionally, the geometry and construction of the screens has received little attention. There is a large opportunity here for testing alternatives to the standard woven wire screen. Future studies should include testing of stamped or printed panels, accordion style shield and retractable screens which could be incorporated into smart homes. It is also worth investigating testing fire resistant coatings on traditional or more easily and cheaply produced materials.

2.7 – Project Outline

After examining the current research being done in the area of bushfire spread through firebrand propagation there were two key areas which, to date, have received minimal or no attention.

2.7.1 – Firebrand Fuel:

While there is a lot of research into the passage of firebrand through screens there has been little focus on the fuel used to create the firebrands. There are several major institutions around the world conducting firebrand research and each of them will be seeking solutions for their own particular area. A key example of this is that NIST in the US has issues with bushfires in several different types of forest, BRI in Japan is more focussed on urban fires, both of which will give off different types of firebrands. Forest fires might include firebrands consisting of conifer needles, different bark types and different timber types whereas urban fires may include processed timbers and polymers mixed with processed chemical.

2.7.2 – Screen Type:

The other major area which has received minimal focus is ideation and testing of different screen types, or even alternatives to screens. Most fire regulations have been implemented using wire mesh with a prescribed opening size as a requirement for houses in bush fire prone areas. With new advances in technology, materials science and manufacturing processes progressing so quickly it is worth revisiting the prescribed metal mesh, perhaps seeking one or more alternatives which are cheaper to manufacture as well as easier and more flexible in fitting to a dwelling.

2.7.3 – Follow on Considerations

As with any research project it is necessary to consider how this work can affect the environment, the industry and society and what follow on consequential effects may be expected.

2.7.4 – Sustainability:

The materials and processes used in making new screen alternatives already consider environmental impact and sustainability. Materials for screens will be selected from those with known end of life structures such as recyclability or reusability. Current screens, being made mostly from stainless steel have a high environmental impact in mining the ore and high energy requirement through production. Alternative materials to be considered, whilst still requiring energy to manufacture, will have a lower energy requirement for production. All materials selected will need to be resilient and have a long operational lifespan.

2.7.5 – Safety:

Materials selected for testing will provide the inherent required safety features, as per AS3959, that being that they are resistant to fire and firebrand.

The materials will be declared safe for human use and interaction, in and around any dwelling. The will be chemically inert through normal use, and under extreme heat and fire conditions.

2.7.6 – Ethical considerations:

Throughout the whole research, design and testing process a strict code of ethics will be adhered to. This will take into consideration the strictest guidelines from the Engineers Australia code of Ethics, the University of Southern Queensland code of Ethics where the ESS apparatus is situated, and the strongest moral code, as presented by the tester.

While products being tested may be constructed from materials which currently exist in the market, any designs tested will be the sole creation of the researcher, not taken from any other proprietary design.

Utmost integrity will be used in testing and reporting of test results. If the designs tested have potential for further application, then further testing may be undertaken by an unbiased and qualified third party, for validation of results.

2.8 – Project Objectives

The focus of this project will be to create and test alternative styles of firebrand shielding for dwellings in bushfire prone areas.

It is proposed that while the current mesh standard is mostly suitable, there are alternative options which may be:

Less expensive to manufacture and install

More flexible and adaptable to different areas in a dwelling

Easily adapted to applications other than firebrand protection

Serve other purposes in a dwelling, such as air flow, glare reduction, pest protection.

To meet the objectives listed, the materials tested will meet two criteria in which current metallic screens are limited. The screen materials will be flexible and, by comparison to metallic screens, inexpensive to manufacture and install.

Current screens focus largely on securing openings in the dwelling, mostly windows and doors. There are however a great many other areas of ingress for burning embers to set the dwelling on fire. It should also be noted that even if embers fail to enter the dwelling, there are often a multitude of other flammable items within the vicinity which might ignite when coming into contact with burning embers.

Flexible and cost effective screens could be produced in larger sheets, covering a much larger area such as surrounding gardens and dead litter. Screens which are flexible can be rolled up and attached to mechanical or even smart home mechanical devices, where they could be activated remotely. Many homes, especially in Australia, have large outdoor living spaces such as verandahs or gazebos. These areas could easily be protected with large, inexpensive screens mounted on roller mechanisms. Having the screens on rollers means they could also be retracted when not needed, allowing greater airflow through the area.

The materials include a well designed and tested flame retardant foam which is currently used for close quarters applications where a foam fire would be catastrophic.

Other materials to be tested are a range of readily available mesh sheets, typically used for commercial, construction or long life exterior applications. The screens have high UV resilience and some level of fireproofing. These mesh screens will be treated with fire retardant spray before testing.

3 – Methodology

3.1 – Materials Selection

The materials selected for testing were chosen due to several reason. Given the timeframe of the project the predominant reason for material selection was the timeframe of availability.

Fire Proof Foam	Shade Cloth – 70% Block out	Outdoor Roller Blind Canvas
5mm thick	Natural / Untreated	Natural / Untreated
10mm thick	Treated – Fire retardant spray 1	Treated – Fire retardant spray 1
15mm thick	Treated – Fire retardant spray 2	Treated – Fire retardant spray 2
20mm thick		
25mm thick		
30mm thick		

3.1.1 – Fire proof foam

This foam was selected from a Brisbane company that had developed this foam over years of research and testing many variations of advanced foam. Prior to selection in this study the foam had passed testing, as part of a whole mattress design, by the C.S.I.R.O as well as several rounds of successful testing at the factory site with direct flames in excess of 1000°C. Under direct flame conditions where a normal foam would quickly become engulfed in flame, this foam suffered only very minor charring as it had an additive which inhibited the flame from starting.

Several pieces of foam were procured, each at 650mm x 650mm square and at several different thicknesses, namely 5mm, 10mm, 15mm, 20mm, 25mm and 30mm. If the foam were tested successfully, it would be more easily applicable to a dwelling if in very thin sheets. Also, as the foam is costed by volume it is preferred to find the thinnest sheet which will test successfully.

The other reason for obtaining several thicknesses of foam for testing is due to the inherent weakness of foam whereby it is susceptible to breaking and tearing with minimal force. This is also the main reasoning for testing other materials. If successful, the secondary materials can be used as a support webbing for the foam. It was proposed that a composite material, created by joining the foam and secondary material, would have the desired properties of not only being fire resistant but also resilient to repeated and regular use.

3.1.2 – Shade Cloth

Shade cloth was selected as it fitted several of the desired criteria. It is relatively cheap, widely produced, readily available and has a large open weave, making it a light material which allows air flow though it. If the testing is successful, shade cloth would provide an excellent support webbing material for the foam. The shade cloth was tested in three states, untreated, treated with fire-retardant spray #1 and treated with fire-retardant spray #2. Please find details of the fire proofing sprays in Appendix D.

3.1.2 – Outdoor Roller Blind Canvas

This material was selected for its main point of difference with the shade cloth, that being that it has a much tighter weave. It is also relative inexpensive, easily produced and readily available. Another advantage of this materials is that there are already fixtures available which have been designed to deploy it in a dwelling, as the title suggests a roller blind mechanism. Successful testing of this material, combined with successful thin foam sheet testing could provide a potential composite material for further testing. The canvas was treated with the same two fire retardant sprays as the shade cloth. Please find details of the fire proofing sprays in Appendix D.

3.1.3 – Wood chip Selection

In order to keep the testing focused primarily on the potential screen materials it was decided not to select a large range of wood chip types. For this research, two wood chip types were selected, Cypress Pine and a Eucalyptus Mix. These were chosen to represent a quick burning softwood, the Cypress, and a denser, slower burning hardwood, the Eucalyptus mix. By selecting a varied set of wood chip types it would allow the test pieces to undergo testing from varied firebrand sizes and densities as well as varied burning qualities such as heat output and resistance to being extinguished.

A standard 300 gram sized portion of cypress wood chips can be seen in Figure 3.1, also showing the comparative size of the fire box with the 300 gram sample inside, ready to commence the test.

Figure 3.1 – Cypress wood chip sample, 300 grams.

3.2 – Current Firebrand Testing Worldwide

In order to obtain meaningful results it is necessary to observe current testing method which are currently being used. By using a similar testing method it will be possible to draw meaningful conclusions from the results of this test set, against other test sets.

Currently, there are two reputable international facilities which are set up to conduct accurate testing, NIST in the US, and BRI in Japan.

3.2.1 – NIST – National Institute of Standards and Technology, USA.

Located at their campus in Gaithersburg, Maryland, USA, NIST has created a firebrand generator capable of sending a shower of firebrand over a test object. This firebrand generator, nicknamed the Baby Dragon, has been used in extensive testing of both in the US, and in partnership with BRI in Japan, one example of which can be seen in Figure 3.2, which shows traditional Japanese roofing material, water reed thatch, being testing against a shower of firebrand. Testing with this apparatus has ranged from overall firebrand shower observation to more specific firebrand testing through fireproof screens.

Figure 3.2 – Testing a sample of water reed thatched room with NIST Fire Brand Generator.

(https://www.nist.gov)

3.2.2 – BRI – Building Research Institute, Japan.

Constructed by Kawasaki Heavy Industries Ltd in 2012, the Fire research wind tunnel, as seen in Figure 3.3, is part of the Japanese Building Research Institute testing facility. This is a much larger, and more versatile wind tunnel which has been used for gaining a deeper understanding of firebrand behavior in and around buildings. While other parts of the world strive to solve issues with firebrand production and interaction at the WUI, the BRI in Japan has conducted more testing which is based around fire propagation through urban areas and high rise buildings. (https://www.kenken.go.jp).

Figure 3.3 – Fire Research Wind Tunnel, used by Building Research Institute, Japan.

https://www.kenken.go.jp/english/information/introduction/facilities/shosai/03.html

3.3 – Ember Shower Simulator

Located at the University of Southern Queensland (UniSQ), Toowoomba, Queensland is a similar apparatus based on the same principles as the NIST Baby Dragon and the BRI Fire Research Wind Tunnel, aptly named the Ember Shower Simulator (ESS). This device is set up to provide a finite number of firebrand for each test. To date, this device has been used for a multitude of tests ranging from:

- Testing firebrand behavior through various metallic mesh screens.
- Ember behavior after passing through screens.
- Effectiveness of metallic screens against firebrands.
- Passing firebrand created by various fuel sources through metallic screens.

The ESS is set up as a wind tunnel which passes a controlled wind over a burning fuel source, which then collects the firebrand from said source and propels it toward a test piece. It's basic design, as seen in Figure 3.4, is a large diameter wind tunnel with a variable vane which allows the operator to change the amount of air which is fed down over the burning fuel source. The air is constricted through a narrowing section, thereby elevating the wind speed and creating a partial vacuum which draws the firebrand up into the outlet section. It has built-in framework which allows a 200mm x 200mm square test material piece to be secured inline on the outlet section. This section is designed to hold metallic mesh screens which allow a high degree of airflow through them. For this test however that framework is not suitable as the materials being tested will not allow a sufficient air flow through them, and the wind tunnel will not function as it's designed to.

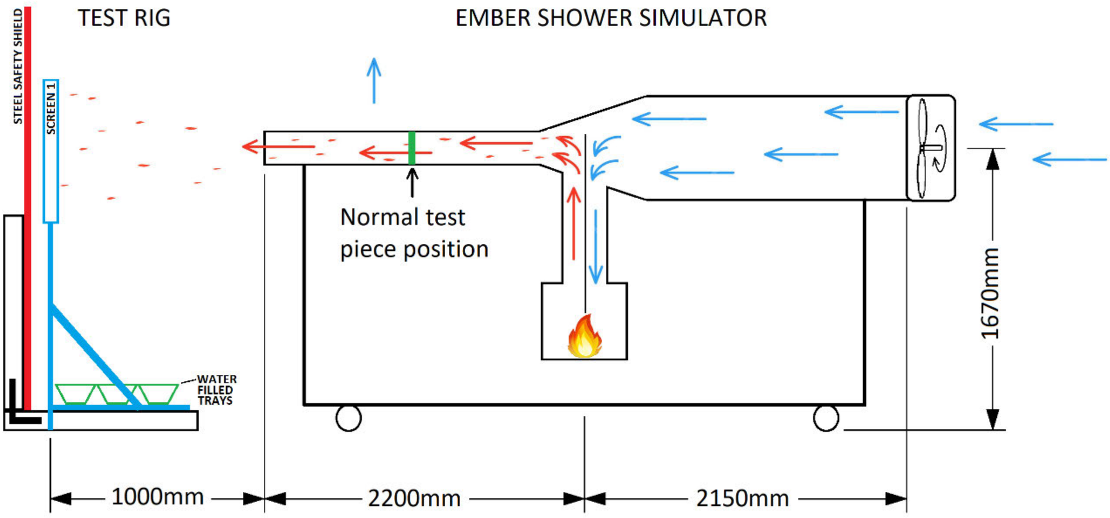


Figure 3.4 – Ember Shower Simulator (ESS). UniSQ Toowoomba, Australia.

In order to facilitate testing for this project a secondary test rig apparatus was created. The test rig is placed at the end of the ESS and subjects the test piece to the flow of firebrand exiting the wind tunnel. By placing the test rig at the correct distance from the ESS exit it is possible to simulate the desired wind speed for which the firebrand will impact the test piece. For this project, the test rig was placed at 1000mm which created an average impact wind speed of 11m/s, thereby simulating the elevated wind speed which exacerbates most bushfires.

Figure 3.5 – ESS setup with test rig during testing, round 1.

3.4 – Test Rig

The test rig is designed to hold the test piece at the correct height, at the outlet of the ESS. It consists of a basic core frame made of two standard pallets fastened together at right angles with a steel shield wall designed to restrict firebrand flow beyond the boundaries of the testing area. The basic timber framework which sits atop the base pallet has a square section on the top which holds a removable frame, in which the test material can be secured between two square timber frames. The whole testing setup including the test rig and test piece can be seen in Figure 3.5, while Figure 3.6(a) shows the removable test frame more clearly, in this case holding the blue testing material, a sheet of 10mm thick fire proof foam. The test rig with the frame for holding the test materials is shown in Figure 3.6(b). Close observation here will show a fine chicken wire mesh in the square frame which is included to limit the flex in the test material during the test. The space beneath the test piece has been designed to hold several trays filled with water, the purpose of which is to collect any firebrand which, after striking the test piece, fall directly down. The water will extinguish the lit firebrand allowing later analysis of firebrand size.

Figure 3.6 – (a)Test rig assembly including water pans. ***(b) Test rig assembly without test piece.***

During the first round of testing, it was observed that the firebrand was only instantaneously in contact with any of the foam test pieces before ricocheting off. This meant that the foam was not being subjected to the firebrand sufficiently enough to be able to ascertain its effectiveness as a fire proof screen material. As such, the test rig was altered prior to the second round of testing. The alteration to the test rig was the addition of a second testing framework attachment, situated in a horizontal alignment just above the water trays, as can be seen in Figure 3.7. This allowed the firebrand that bounced off the vertical test piece to fall down, and rest on the horizontal test piece until they either burned through or were extinguished. Final tests conducted on the day were on angled test pieces. This required a second change to the test rig where the square test piece holder was angled backward at 20º past the vertical position. The reasoning for including this testing was to mimic any and all conditions that any potential fire proof sheet might be subjected to. For instance, it is unreasonable to assume that a fire proof sheet would be in a perfectly vertical or horizontal position indefinitely. Even if fasteners were used to hold said sheet in place it is possible that volatile environmental conditions that could easily be expected in a bushfire situation would flap and move the fire proof sheet into different positions, possibly freeing it from part or all of its fasteners.

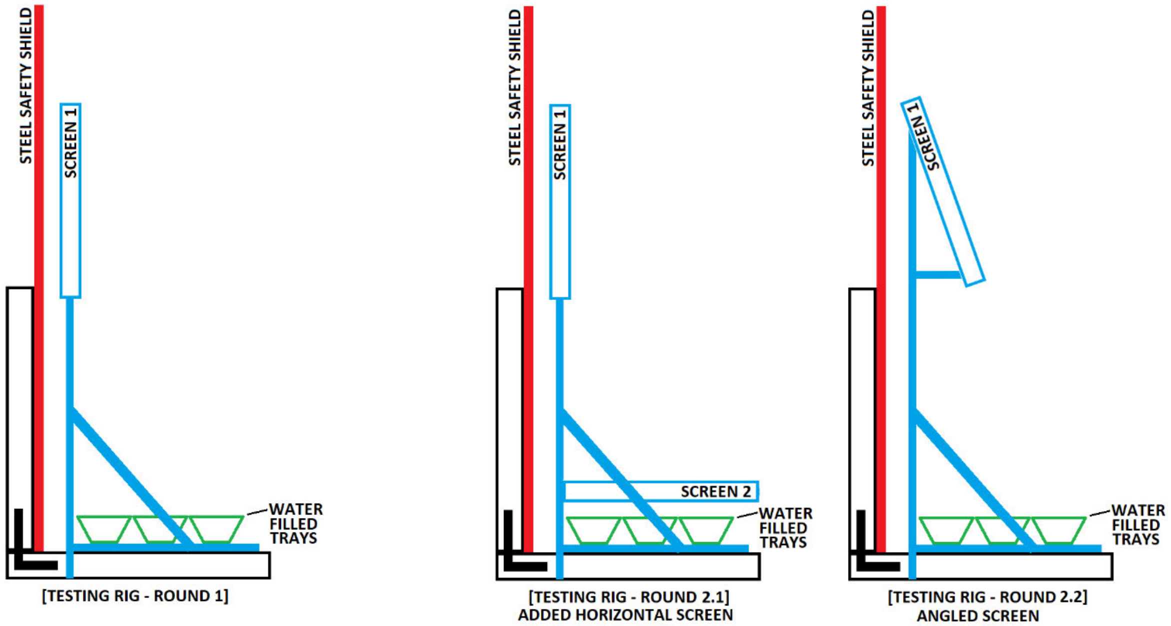


Figure 3.7 – Test Rig changes from round 1 testing session to round 2 testing session.

3.5 – Test Session Preparations

Pre-planning prior to testing sessions required the completion of several key steps, ranging from administrative applications to construction and procurement of materials.

3.5.1 – Risk Management Plan (RMP) and Hot Work Permit (HWP)

As the testing sessions would require the use of live fire and firebrand it was necessary to complete a RMP which thoroughly analysed all aspects of the testing for potential risks to the operator/s and surrounding infrastructure and environment. The complete RMP can be found in Appendix C, and covers all possible risks ranging from ember and fire burns to the operator to extended exposure to UV radiation from testing in an outdoor setting. Accompanying the RMP is a hot work permit (HWP) which covers risks directly associated with hot works on UniSQ campus such as welding and grinding. Welding and grinding will produce metallic sparks which can linger and be a cause of ignition after a delayed period and in a similar manner, this study would be producing firebrand which can also have a delayed ignition effect. Because of this similarity, the HWP was required. Please find the HWP in Appendix B.

3.5.2 – Personnel Required

The ESS is mounted on wheels and can be rolled from the storage area to the testing area however it is still so large that it requires a minimum of two people to safely move it from one location to another. Additionally, as per the RMP testing must only proceed with an operator plus an additional trained person to act in the role of spotter, someone who can independently monitor the test, watching for errant firebrand travelling past the boundaries of the test area. For each testing session it was necessary to coordinate with a trained UniSQ laboratory technician to be present to assist for the duration of the testing session.

3.5.3 – Weather Considerations

Pre-planning of the testing period as a whole meant all testing sessions should be completed between July 2023 to September 2023 in Toowoomba, Queensland. In this region these months typically consist of cool to mild weather which would not predictably provide any challenges to planning the testing sessions. The only consideration would be local rain events which would have to be monitored much closer to any planned testing session. The weather forecast was monitored via the Bureau of Meteorology mobile phone app which provided mostly reliable predictions and a live radar map of the local area.

3.5.4 – Test Rig

While the ESS was already constructed and ready for use it was necessary to construct an additional testing rig. There was no need for this to be aesthetically pleasing, only function and as such it was constructed using readily available, sturdy but inexpensive materials:

- Two timber pallets, free from local hardware store.
- Timber for construction of test screen holder + test screens x3 – Used timber readily available to author. (Excess queen bed slats).
- Fine wire mesh (chicken wire). Purchased from hardware store.
- Steel brackets and screws to attach pallets together. Purchases from hardware store.
- Reclaimed corrugated steel roofing sheets. Four of, purchased from scrap yard.

3.5.5 – Test Materials

The following is a list of materials procured for testing.

- Fire proof foam. All test pieces cut to fit into test frames at 650mm x 650mm. Two sets, each consisting of six thicknesses – 5mm, 10mm, 15mm, 20mm, 25mm and 30mm. This was supplied, free of charge by the manufacturer.
- Shade Cloth, 70% block out level. A 5000mm x 1200mm roll purchased from a hardware store. Light colour was chosen to more easily see any damage inflicted during testing.

- Outdoor canvas roller blind. Purchased from hardware store. Light colour was chosen to more easily see any damage inflicted during testing.
- Fire retardant spray 1. Purchased from reputable company online. Details in Appendix D.
- Fire retardant spray 2. Purchased from Brisbane based company. Details in Appendix D.

3.6 – Testing Schedule

Date	Run	Test piece material	Test piece detail	Test piece alignment
ROUND 1				
30/08/23	1	Foam	5mm thick	Vertical
30/08/23	2	Foam	10mm thick	Vertical
30/08/23	3	Foam	30mm thick	Vertical
30/08/23	4	Shade Cloth	Untreated	Vertical
30/08/23	5	Shade Cloth	Treated: Types 1&2	Vertical
ROUND 2				
6/9/2023	6	Roller blind Canvas	Treated: Types 1&2	Vertical
		Foam	5mm thick	Horizontal
6/9/2023	7	Roller blind Canvas	Treated: Types 1&2	Vertical
		Foam	5mm thick	Horizontal
6/9/2023	8	Roller blind Canvas	Untreated	Vertical
		Roller blind Canvas	Treated: Types 1&2	Horizontal
6/9/2023	9	Foam	5mm thick	Vertical
		Roller blind Canvas	Untreated	Horizontal
6/9/2023	10	Foam	20mm thick	Vertical
		Foam	5mm thick	Horizontal
6/9/2023	11	Foam	10mm thick	Vertical
		Foam	20mm thick	Horizontal
6/9/2023	12	Foam	15mm thick	Vertical
		Foam	10mm thick	Horizontal

6/9/2023	13	Roller blind Canvas	Treated: Types 1&2	20º angle
6/9/2023	14	Roller blind Canvas	Treated: Types 1&2	20º angle
6/9/2023	15	Foam	15mm thick	20º angle
6/9/2023	16	Foam	15mm thick	20º angle

Figure 3.8 – Testing schedule for both Round 1 and Round 2 of testing.

4 – Results

Testing was conducted over two sessions with the first session used to ascertain the eligibility of the proposed materials and testing methods. During the first testing session it was observed that the embers were instantaneously bouncing off and therefore not in contact with the foam test piece for a period long enough to test the foam's suitability as an ember shield. It was decided that the test rig would need to be altered to accommodate a horizontal, and angled testing piece, which would allow the embers to be in contact with the foam for a sufficiently long enough period. The secondary reason for allowing for testing of the foam at different angles is that this would more accurately mimic a real-life application of a potential ember-proof screen, as it might be installed on a dwelling.

4.1 – Testing Schedule and Results

Date	Run	Test piece material	Test piece detail	Test piece alignment	Duration (mm:ss)	ESS wind speed (m/s)	Wood chip type	Wood chip mass (grams)	Burn Pile Temp. (°C)
ROUND 1									
Conditions		***Temperature: 22°C - 24°C***		***Humidity: 40% ± 1%***		***Wind Speed: 3.9m/s ± 2m/s***		***Wind direction:***	***N/NNW***
30/08/23	1	Foam	5mm thick	Vertical	08:56	12 ± 1	Cypress pine	300	270±5
30/08/23	2	Foam	10mm thick	Vertical	07:32	12 ± 1	Cypress pine	300	270±5
30/08/23	3	Foam	30mm thick	Vertical	08:05	10 ± 1	Cypress pine	900	270±5
30/08/23	4	Shade Cloth	Untreated	Vertical	06:06	10 ± 1	Cypress pine	300	270±5
30/08/23	5	Shade Cloth	Treated: Types 1&2	Vertical	06:21	10 ± 1	Cypress pine	300	270±5
ROUND 2									
Conditions		***Temperature: 24°C - 27°C***		***Humidity: 45% ± 1%***		***Wind Speed: 1.9m/s ± 1m/s***		***Wind direction:***	***N***
6/9/2023	6	Roller blind Canvas	Treated: Types 1&2	Vertical	02:15	11 ± 1	Cypress pine	300	no data
		Foam	5mm thick	Horizontal					
6/9/2023	7	Roller blind Canvas	Treated: Types 1&2	Vertical	08:38	11 ± 1	Eucalyptus hardwood	300	no data
		Foam	5mm thick	Horizontal					
6/9/2023	8	Roller blind Canvas	Untreated	Vertical	07:56	11 ± 1	Eucalyptus hardwood	300	no data
		Roller blind Canvas	Treated: Types 1&2	Horizontal					
6/9/2023	9	Foam	5mm thick	Vertical	07:24	11 ± 1	Eucalyptus hardwood	300	no data
		Roller blind Canvas	Untreated	Horizontal					
6/9/2023	10	Foam	20mm thick	Vertical	09:36	11 ± 1	Eucalyptus hardwood	600	no data
		Foam	5mm thick	Horizontal					
6/9/2023	11	Foam	10mm thick	Vertical	10:17	11 ± 1	Eucalyptus hardwood	600	no data
		Foam	20mm thick	Horizontal					
Conditions		***Temperature: 25°C - 28°C***		***Humidity: 45% ± 1%***		***Wind Speed: 3.2m/s ± 2m/s***		***Wind direction:***	***NNW***
6/9/2023	12	Foam	15mm thick	Vertical	08:42	11 ± 1	Eucalyptus hardwood	600	no data
		Foam	10mm thick	Horizontal					

Table 4.1 – Testing Schedule and results, with local testing conditions. ***(continued on next page)***

ROUND 2 - continued									
Date	Run	Test piece material	Test piece detail	Test piece alignment	Duration	ESS wind speed	Wood chip type	Wood chip mass	Burn Pile Temp.
					(mm:ss)	(m/s)		(grams)	(oC)
6/9/2023	14	Roller blind Canvas	Treated: Types 1&2	20^o angle	05:13	11 $\pm$ 1	Eucalyptus hardwood	600	no data
6/9/2023	15	Foam	15mm thick	20^o angle	05:09	11 $\pm$ 1	Cypress pine	600	no data
6/9/2023	16	Foam	15mm thick	20^o angle	05:22	11 $\pm$ 1	Eucalyptus hardwood	600	no data

Table 4.1 – Testing Schedule and results, with local testing conditions. (continued on previous page)

The testing facility was located in Toowoomba, Queensland. The details of the local, ambient weather conditions as listed in Table 4.1 were taken from the Australian Bureau of Meteorology mobile app at the time of testing and were regularly checked throughout the testing period.

4.2 – Ember Details

During testing two types of wood chip were used to create the embers, these being Cypress pine and a Eucalyptus hardwood mix. Both lots were dried for 8 hours at 100°C to remove excess moisture. This was done as both an aid to better burning and as a safety precaution to prevent excessive smoke creation as they burned. Initially a 300 gram portion of wood chips was used for each test run, with the run continuing until all chips were burned. During round 1 of testing an exception was made. Having noticed that the embers had made no impact on the foam it was decided to increase the volume of wood chips, and by extension, the number of embers which would impact the test foam piece. As expected, this created a very dense, longer running ember shower during that test run. During round 2 of testing, it was noticed that the cypress chips were no longer dry, so testing continued with eucalyptus chips while the cypress chips were returned to the oven for drying. The first few test runs with 300 grams of the eucalyptus chips generated a much lower quantity of embers than the same amount of cypress wood chips. To ensure that the foam was tested properly the volume of eucalyptus chips was increased to 600 grams for subsequent test runs. It was found that 600 grams of eucalyptus chips provided a comparable quantity of embers to the earlier test runs with 300 grams of cypress chips.

The operating conditions and settings on the apparatus remained unchanged for each test run, the only exception being a slight realignment to the fan after test run 2, which resulted in a slightly lower wind speed. As the operating conditions were largely unaltered and the volume of wood chips used only changed twice it is assumed that the quantity of embers produced per wood chip type and mass would be suitably represented by any single test run.

4.2.1 – Wood Chips

The wood chips used were all processed through the same wood chipper and the size distribution for both the eucalyptus and cypress is very similar, as shown in Table 4.2. A typical 300 gram selection of eucalyptus wood chips can be seen in Figure 4.2, with the size distribution shown in Figure 4.2.

CYPRESS	Quantity	Mass (grams)	Average Mass/Pce (grams)	**EUCALYPTUS**	Quantity	Mass (grams)	Average Mass/Pce (grams)
Super Large	3	16	5.333	Super Large	5	26	5.200
Very large	7	21	3.000	Very large	6	23	3.833
Large	13	23	1.769	Large	18	26	1.444
Medium	22	30	1.364	Medium	25	29	1.160
Small	52	48	0.923	Small	45	41	0.911
Very Small	188	89	0.473	Very Small	168	87	0.518
Tiny	523	73	0.140	Tiny	422	68	0.161
Total	*808*	*300*	*0.371*	*Total*	*689*	*300*	*0.435*

Table 4.2 – Unburned wood chip mass distribution and quantity

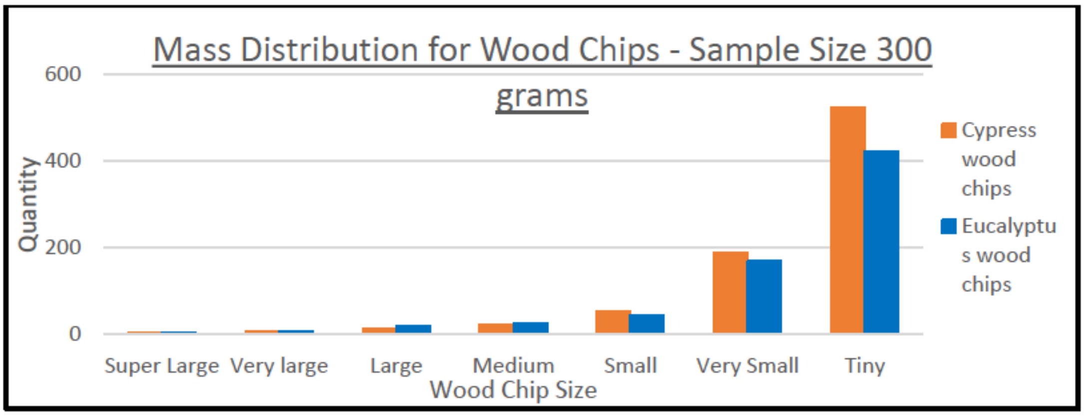


Figure 4.1 – Mass distribution for 300 gram sample of both wood chip species.

Figure 4.2 – A 300 gram sample of unburned wood chips – Eucalyptus hardwood mix.

Figure 4.3 – Size distribution of a 300 gram wood chip selection – Eucalyptus hardwood mix. (a)Super Large, (b)Very Large, (c)Large, (d)Medium, (e)Small, (f)Very Small, (g)Tiny.

4.2.2 – Ember Production

The quantity of embers produced is significantly higher than the quantity of wood chips used. As the wind is forced into the fire chamber it not only accelerates the wood burning process but also removes the exterior, burning sections of the wood chips, evidently creating embers which are notably smaller than the wood chip they came from. It can be seen in Figure 4.4 and Figure 4.5 that the production of embers over tends to the same pattern, irrespective of the wood chip type. At the commencement of the test there are fewer burning wood chips which typically provides a slow increase to ember production. As the test progresses, the wood chip pile undergoes a greater percentage of burning chips which produces a larger amount of embers. The process culminates in an abrupt manner with the exhaustion of the fuel supply.

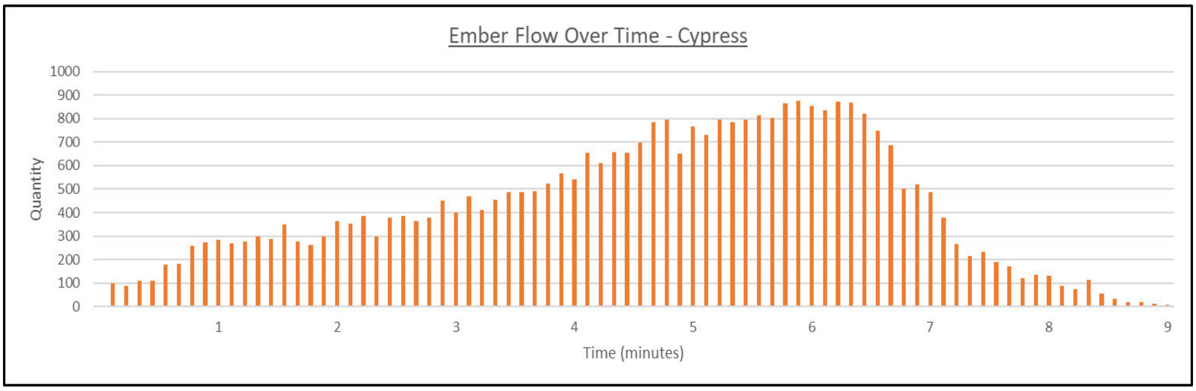


Figure 4.4 – Ember flow over time –300 grams cypress wood chips.

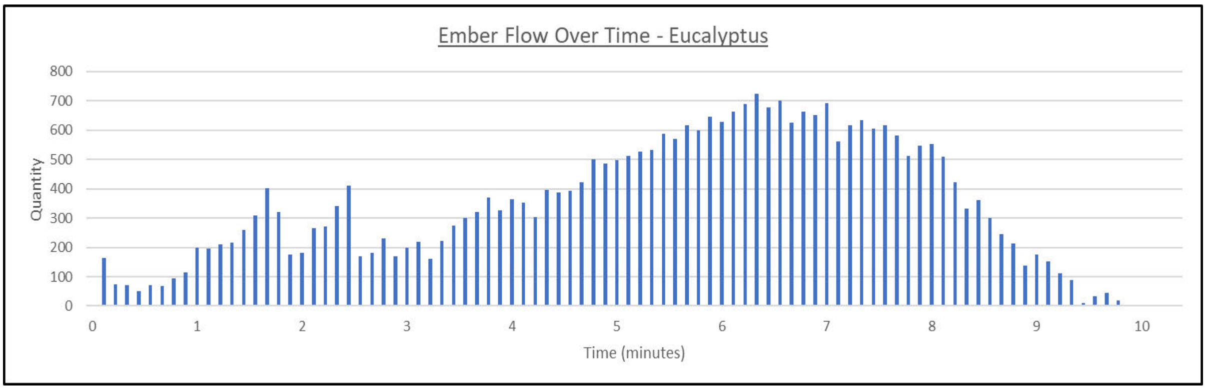


Figure 4.5 – Ember flow over time — 600 grams eucalyptus wood chips.

When comparing the two types of wood chips it is possible to see that the cypress chip supply is exhausted before the eucalyptus chip supply. The apparent difference in burning behavior is easily understandable when considering that hardwoods, such as Eucalyptus varieties will tend to burn slower and produce a higher heat output than softwoods, such as Cypress pine. (ultimatefires.com.au) The cypress chips burned quicker and created smaller embers. When observing the two sets of data it can be seen that a 300 gram sample of cypress wood chips produced a comparable amount of embers to a 600 gram sample of eucalyptus wood chips, as seen in Figure 4.6. The ember count over each test period show that the cypress pine chips burned quicker and produced a higher number of smaller embers, while the eucalyptus wood chips took longer to burn to a point where they would produce embers, and produced a steadier flow of embers.

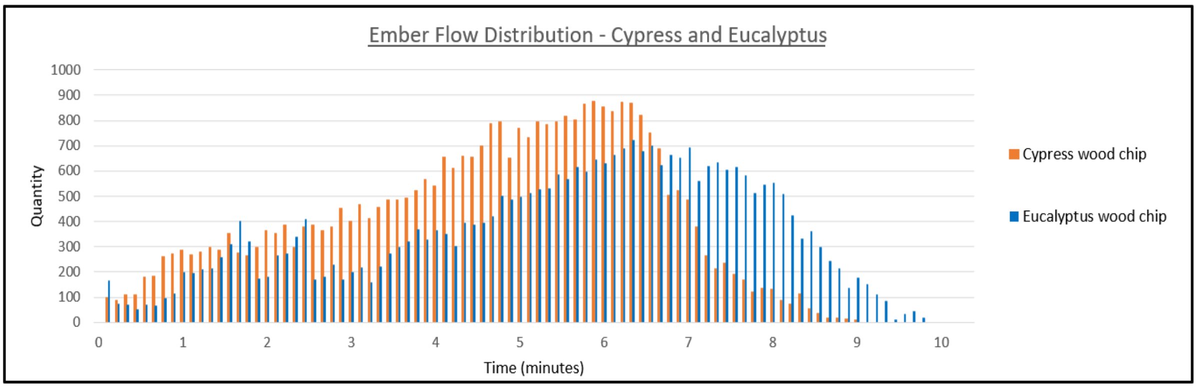


Figure 4.6 – Ember flow over time – Cypress and Eucalyptus ember comparison

4.3 – Foam

The foam samples were tested under different conditions to assess the suitability of the foam for use in varied conditions. Not only were the tests conducted using two variations of ember fuel source, the cypress and eucalyptus wood chips, but the foam was held at different angles, allowing the embers to impact and interact with the foam in different ways.

Initial testing was done with the foam test piece placed vertically, but slow motion video recording of this testing showed that the embers tended to ricochet off the foam, due to the inherent elasticity of the foam. Further testing subjected the test pieces to ember attack at both a 20o backward incline, and at a horizontal inclination, where the embers striking a vertical test piece would bounce off and fall onto the horizontal test piece. This allowed the embers to rest against the foam for a longer period. During these tests water pans were placed under the horizontal test piece to capture any embers which burned through.

4.3.1 – Vertical tests

When tested in a vertical position the foam samples suffered 0% deformation or burns. The only change to the test piece at the completion of the test was a discolouration to the surface which was caused by the oils and soot in the wind tunnel caused by burning wood chips.

There were two extreme tests cases where the foam would have been most likely to suffer burn marks or deformation. The first case is test run 3 where the wood chip fuel load was tripled to 900 grams. This eventuated in a much longer and denser ember shower on the 30mm thick foam test piece. Figure 4.7 shows the before and after images of the 30mm foam in this test run. The other case where the foam was most likely to show burns or deformation was test run 9, the 5mm thick foam test piece subjected to 600 grams of eucalyptus embers. The before and after images of this test run can be seen in Figure 4.8.

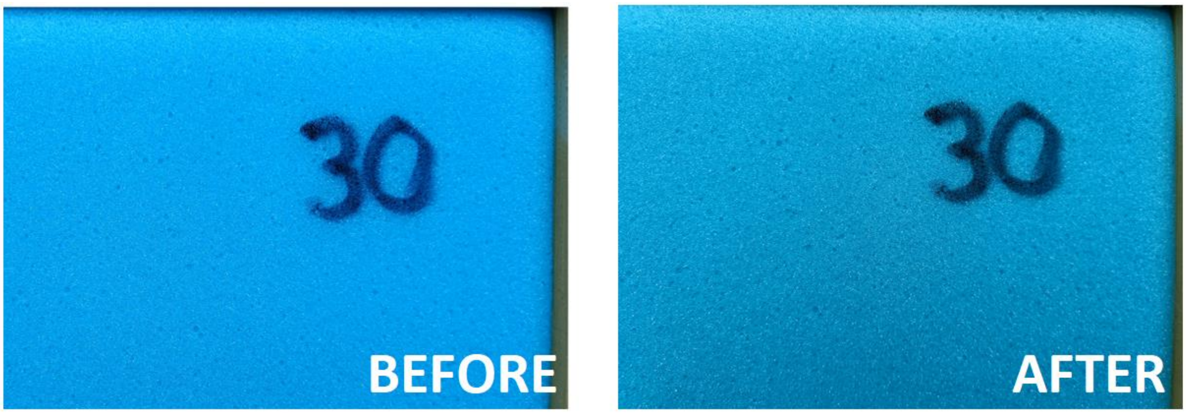


Figure 4.7 – Test run 3 – 30mm thick foam against 900 grams cypress embers.

Figure 4.8 – Test run 9 – 5mm thick foam against 600 grams eucalyptus embers.

4.3.2 – Angled tests

During the angled tests the test piece was reclined backward 20°. The purpose of this was to ascertain if this allowed the flying embers to interact differently with the test piece. It was anticipated that the embers, having impacted the foam at a different angle, could slide along the surface. The results however showed that, exactly like the vertical testing alignment, the angled foam pieces suffered no damage at all. The before and after images of the test piece can be observed in Figure 4.9. It should be noted that the photos in Figure 4.9 were taken whilst sitting in the testing rig and they show shadow patterns which should be ignored.

Figure 4.9 – Test run 16 – 15mm thick foam against 600 grams eucalyptus embers.

4.3.3 – Horizontal tests

It was only in the horizontal alignment that the foam test pieces suffered any damage. This was due to the ember remaining in contact with the test piece for a longer period. After the test it was observed that many of the embers had burned partially through the foam at which point they were extinguished and remained lodged in the foam sheet. While it was expected that the small embers might become extinguished quickly while the larger embers remain alight for a longer period, it was evident from the embedded ember remains that all embers were extinguished quickly, with only very few creating burns deeper than 4mm deep.

Analysis of the foam test piece after testing showed burn marks which varied in area and depth. The area and depth of each mark are recorded and shown in Figure 4.10 for the 5mm foam, Figure 4.11 for the 10mm foam, and Figure 4.12 for the 20mm foam. The initial horizontal test was conducted on the 5mm thick foam sheet. After testing there were many clearly obvious marks where embers had completely burned through. Given that this would make this thickness of foam unsuitable for further applications it was decided to progress to the 20mm thick sheet to see the if the embers would continue to burn completely through it. Completion of the 20mm thick testing showed no burn marks which had burned through the foam sheet. Following this result, the aim was to ascertain how thin the foam sheet could be without suffering burn through, as such the 10mm thick sheet was selected as the next test.

The area and depth data collected from the burn marks in the test sheets was a widely distributed set with multiple outlying points, but overall it tend towards the same pattern for all three tests, with the area of the ember burn tending to correlate to the depth of the burn mark it made. Typically, the larger the surface area of the ember burn, the deeper it was also.

When comparing Figure 4.10 against Figures 4.11 and 4.12, it’s possible to see that the trend for the shallow burns, less than 1mm deep, doesn’t drop as quickly. This indicates that for just this particular test piece, there are a higher number of large burn marks. As the burn marks are not very deep it could be postulated that they are created by small embers with a minimal burning area, yet they still managed to create a burn mark as they were able to draw oxygen through the thinner section of foam. The same embers, having landed on the thicker foam sheets would not be able to draw as much oxygen and would be extinguished much quicker, leaving smaller area burn marks.

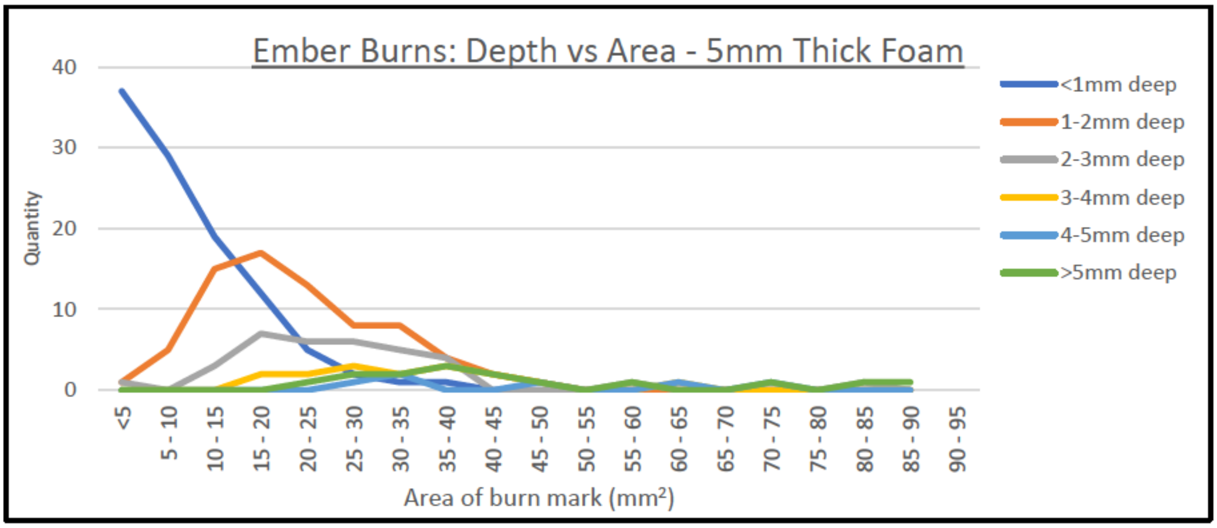


Figure 4.10 – Test run 9 - Area and depth measurements of ember burns in 5mm thick foam.

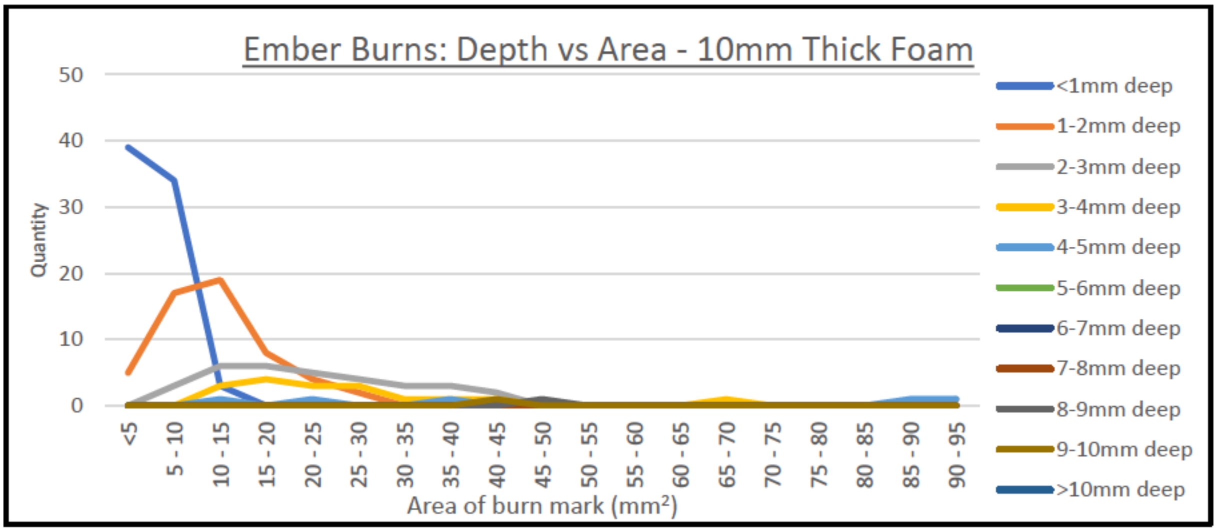


Figure 4.11 – Test run 11 - Area and depth measurements of ember burns in 10mm thick foam.

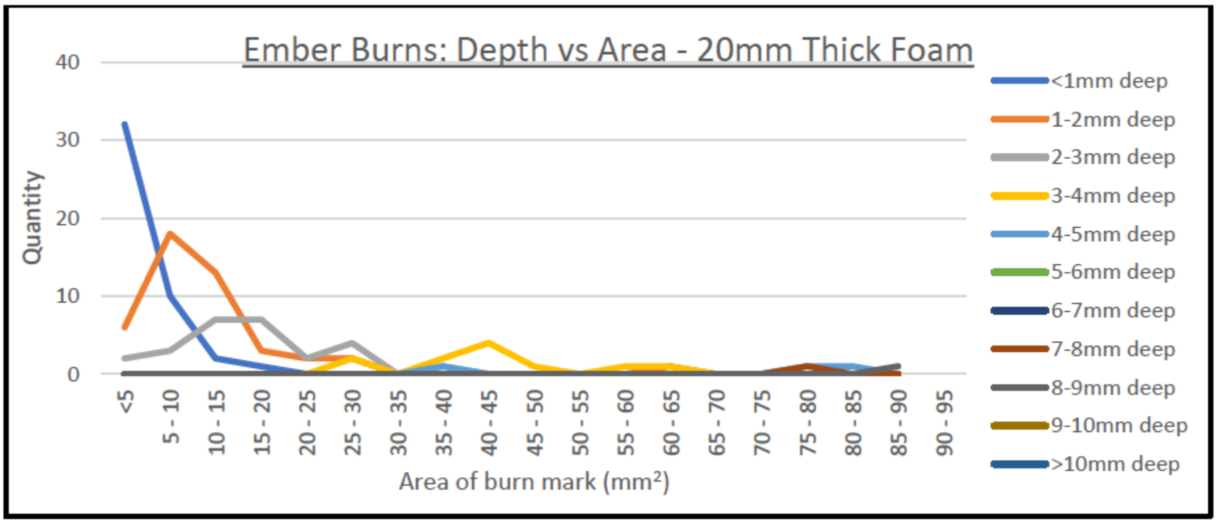


Figure 4.12 – Test run 10 - Area and depth measurements of ember burns in 20mm thick foam.

4.4 – Shade Cloth

There were three variants of the shade cloth submitted for testing, a natural, untreated piece of shade cloth, and two other pieces treated with two different fire retardant sprays designed for synthetic materials. The untreated shade cloth suffered a high amount of deformation from burns, with the two treated test pieces faring only slightly better. As seen in Figure 4.13 The two different fire-proof sprays applied to the shade cloth pieces was ineffective at preventing any damage from the embers. Appendix F for larger photos of test pieces

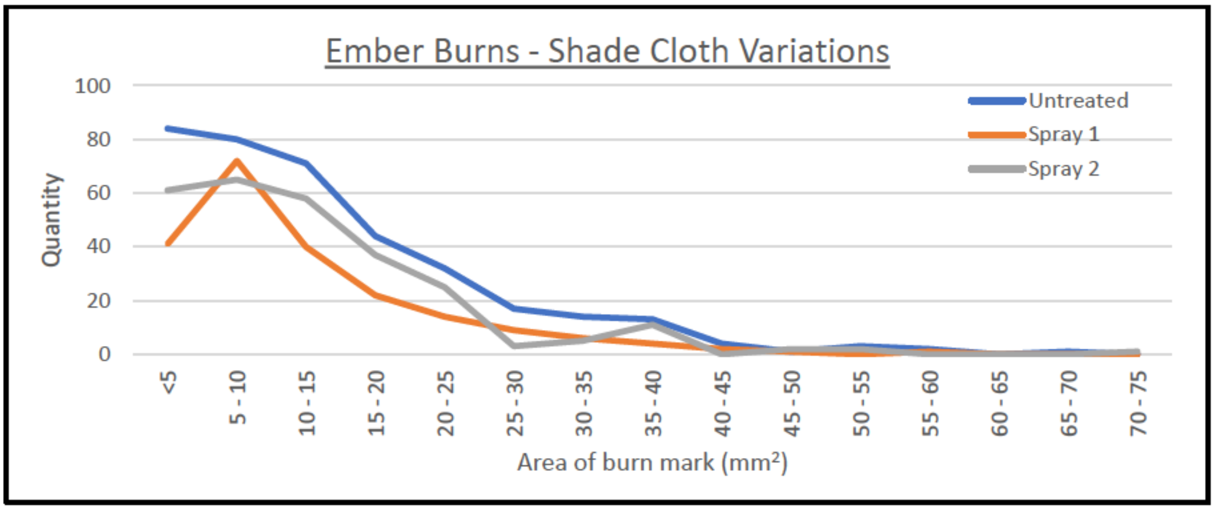


Figure 4.13 – Ember burn area in three shade cloth test pieces.

During the testing the embers would impact the shade cloth in the central area with most sticking and burning through. This was possible due to the highly open weave of the shade cloth which allowed the air to pass through it, rather than buffet against it. A portion of the embers which hit at a distance from the center would slide along the shade cloth and come rest against the wooden frame, there burning through the shade cloth. The burn holes are clearly seen in Figure 4.14, as black marks.

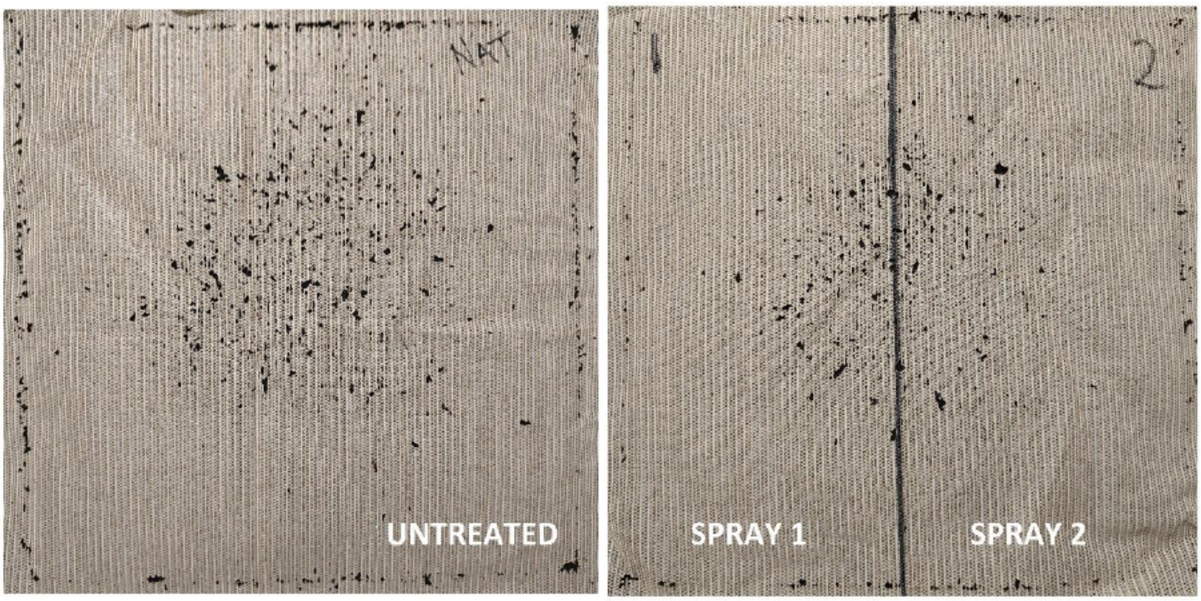


Figure 4.14 – Shade cloth test pieces. Untreated, Treated – Spray 1, Treated – Spray 2.

4.5 – Canvas

The same testing procedure followed with the synthetic outdoor canvas material, with the same three variants used for testing, those being untreated canvas and canvas pieces sprayed with the two different fire retardant sprays.

When tested in a vertical alignment both the untreated and treated canvas varieties performed very well, with no deformation. The results for testing in a horizontal position are shown in Figure 4.15, they show that the untreated canvas was prone to burn marks from the embers while the two fire proof treatments gave the canvas very high resistance to ember attack, with a very low number of burns being found in post test inspection. Please refer to Appendix F for larger photos of test pieces.

The canvas treated with the fire proof sprays was however covered with a notably thicker layer of soot and dirt than any of the other test pieces, due to a sticky film created on the canvas surface by the two different sprays, with Spray 2 creating a much more adhesive layer.

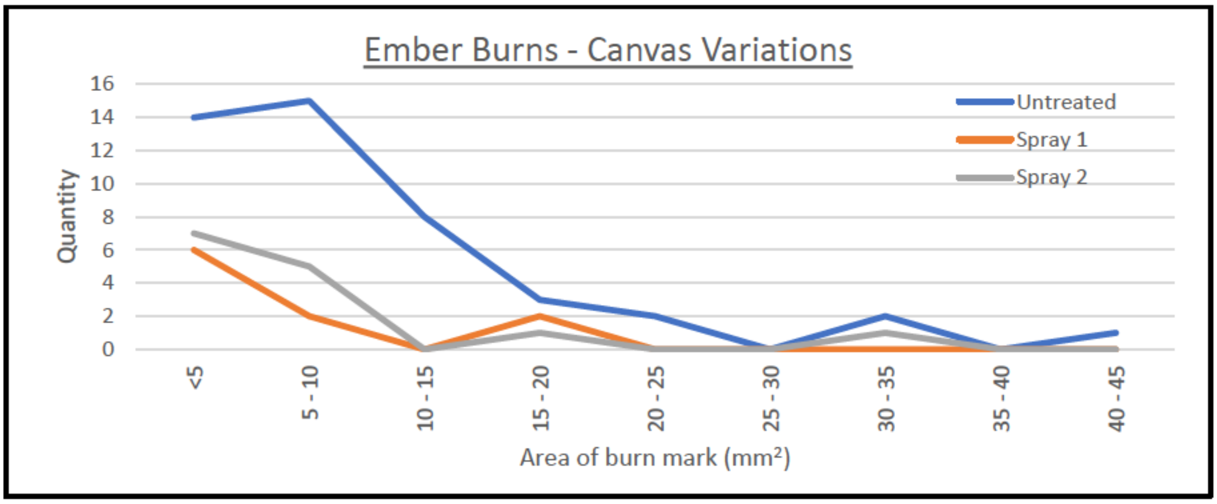


Figure 4.15 – Ember burn area in three canvas test pieces.

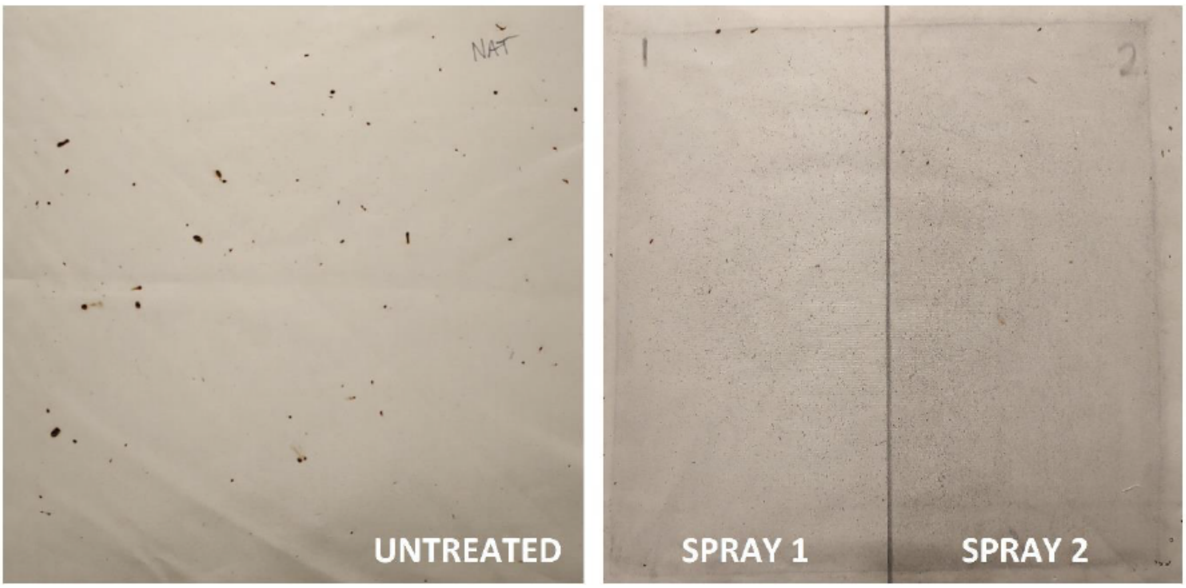


Figure 4.16 – Canvas test pieces. Untreated, Treated – Spray 1, Treated – Spray 2.

5 – Discussion

The testing was mainly focused on ascertaining the suitability of the foam for ember proofing applications and overall, the foam performed well. There are however other aspects of the testing which should be considered including not only the test results from the shade cloth and canvas, but also the testing apparatus used and how well the testing procedure was setup up.

5.1 – Foam

The only differentiation in the many foam samples tested was the thickness in which they were cut. All samples were taken from the same from the same batch and as such are identical in chemical and physical composition. When considering which thicknesses to use as test pieces it was decided that the thinner the foam sheet was, the more versatile it would be for future applications. Discussion with the manufacture allowed that a 5mm section was the thinnest that could possibly be cut from the bun, without suffering deviations in the thickness. As such, the sections used were 5mm, 10mm, 15mm, 20mm, 25mm and 30mm. Not all samples needed to be tested, but having them available for use as needed was necessary for any unseen complications.

5.1.1 – Vertical and Angled Testing

Following all of the vertical and angled tests the foam test pieces showed no burn marks or deformation at all. The only visible difference was a slight discolouration due to the soot and smoke created by the burning wood chips and projected through the wind tunnel alongside the embers. A very close and careful analysis of the surface structure showed no degradation to the cell structure, either from the burning embers or the heat present in the wind. As previously discussed, this was likely due to the fact that the embers were only instantaneously in contact with the foam before ricocheting off.

5.1.2 – Horizontal Testing

When tested in the horizontal position the embers were able to rest against the foam until they either burned through or were extinguished. This allowed a truer representation of the foam's ability to withstand ember attack. After the test was completed, the test pieces were analysed and all burn marks were catalogued by their depth and the area of the burn marks. There is a loose correlation that can be seen in Figures 4.10, 4.11 and 4.12, between the depth and area of the burn marks created. Typically, the larger the burn area the deeper it was. Given the large range in size and non-homogenous nature of the wood chips however there are many outliers which don't follow this pattern. There are several deep burns with a small area which were created but long, thin embers.

5.1.2 – Foam Buoyancy

When considering the differences between the area and depth in the three samples, it's possible to see that the 5mm sample (Figure 4.10) has a slightly higher number of shallow burns. This is likely due to the fact that during testing, many of the embers which created these small burn marks on the 5mm sample simply bounced off the thicker samples. The natural tendency of most foam is to act like a spring. The spring effect in foam is relative to the mass impacting it and the thickness of the section. In the case of a seat cushion for instance, the foam would be cut to 100mm or 150mm to resist the weight of a person, but in the case where the foam is only impacted on by a small ember, weighing only a fraction of a gram, the spring effect changes greatly with each millimeter of foam thickness. In this case, while the 5mm foam still has a spring effect, that effect is much greater in the 10mm and 20mm foam sections. This is likely the reason why the 5mm section shows a greater number of very shallow, small area burn marks.

5.1.3 – Air Flow Through the Foam

Another observable pattern, visible in Figures 4.10, 4.11 and 4.12 is that the 5mm thick foam shows a significantly higher quantity of deep burn marks than the 10mm and 20mm test pieces. When considering only the ember burns deeper than 5mm, the 5mm thick foam shows 5.98% while the 10mm thick foam is only 1.06% and the 20mm thick foam is at 1.52%. Even combining the totals and considering any ember burn mark deeper that 4mm, the 5mm thick foam exhibits 8.37%, with the 10mm and 20mm thick foam pieces at 3.71% and 3.79% respectively. It is reasonable to assume this is due to the greater air flow through the 5mm foam section allowing the burning ember to remain alight for a longer period. This foam, having been designed predominantly for use in mattresses which benefit from increased ventilation allowing a person to sleep 'cooler', was designed as an open cell structure with a high degree of air flow. Despite the high degree of air flow however it is clear to see that the embers on the thicker sections will only burn through so far before becoming extinguished. The deepest burn on any section is between 9mm and 10mm deep. So, while the thinner section of foam may be more desirable for use in ember shield designs, selecting a thicker section will yield better results.

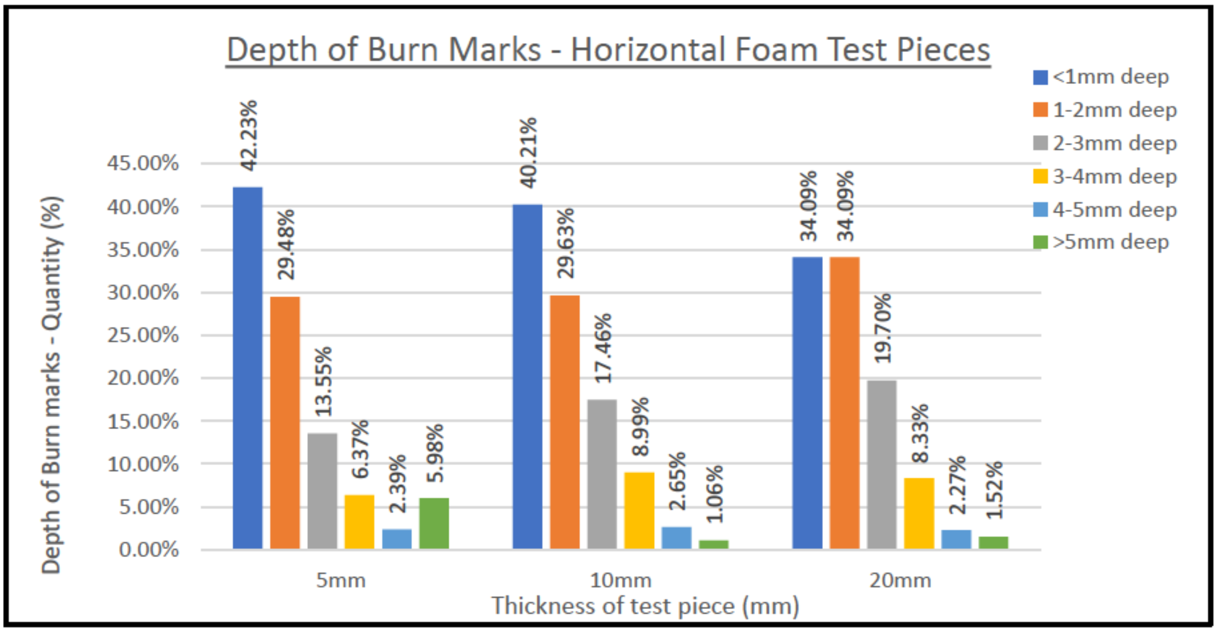


Figure 5.1 – Area and depth of the burn marks in horizontal foam samples.

Overall, the foam performed well against the ember attack. When considering the collected data as a whole, only 1.75% of embers burned deeper than 5mm. The foam is suitable for further testing, but when testing the foam by itself, care should be given to the thickness of the test sample. If testing the foam as part of a composite structure, the composite material should be selected with the air flow and buoyancy of the foam in mind.

5.2 – Shade Cloth

The shade cloth was chosen for testing as it is relatively inexpensive, easy to produce and readily available. If it underwent successful testing it would provide a cost effect way of bracing the foam sheets. The results of the testing show the all three samples of the shade cloth suffered catastrophic failure. The untreated section, as seen in Figure 4.14, shows substantial damage to the main ember impact area in the center, but also considerably damage around the edge, where the shade cloth was held in place by the timber frame. As the shade cloth lacks the natural buoyancy of the foam and allows a greater proportion of the air to flow through it, the embers behaved differently. Instead of bouncing off, they tended to hit the shade cloth near in the center region, then slide outwards until the came to rest against the timber frame. This led to the still burning ember burning through the test piece. The test piece which had been treated with the two different fire retardant sprays did not perform and a noticeably higher standard. The test piece treated with fire retardant spray 1 still suffered 58% of the damage that the untreated sample took, with the spray 2 sample taking 74% of the damage taken by the untreated sample. It is postulated that the reason why neither fire retardant spray had a significant effect is as both fire retardant sprays specified better performance on synthetic materials with a tighter weave.

Shade cloth can be confidently eliminated from any future testing design.

5.3 – Canvas

Like the shade cloth, the outdoor roller blind canvas material was chosen as it is relatively inexpensive, easily manufactured and readily available. In the event of successful testing it could be easily incorporated into a composite material with the foam sheets.

When testing in the vertical and angled positions all canvas test pieces performed excellently, with the untreated sample suffering only minimal, mild singe marks and the treated samples taking no damage at all.

When placed in the horizontal position the untreated canvas suffered many significant burn marks, many of which burned through the material. The canvas test piece that was treated with the two fire retardant sprays remained in good condition, taking only a small amount of damage. It is evident that the tighter weave of the canvas was provided a better surface for the sprays to adhere to with spray 1 sample taking only 22% of the damage taken by the untreated test piece and spray 2 taking 31% of the damage. Figure 4.16 shows the three test pieces after undergoing testing in a horizontal alignment. Full count of burn marks can be found in Appendix F.

The performance of the canvas during testing shows that is has potential for application as an ember attack barrier. If considering this material for further testing however it should be noted that both of the fire retardant treatments are water soluble, and as such not a permanent solution. If a more permanent fire retardant coat is sourced, the canvas could be considered for further testing.

5.4 – Limitations of the Testing process

The scope of the testing process used in this project was quite narrow, with very minimal variation in the process. The testing process was sufficient for an initial testing round on unknown materials which are typically not considered to fire proof, but further testing would benefit from expanding the scope of testing to include greater variation in the test conditions.

Weather

The testing was conducted in an area where the ambient conditions were cool to mild temperatures, gentle breezes and normal humidity. Typically, bushfires thrive in high heat, low humidity and strong winds. Testing the materials in milder weather may give results which will not be repeatable when in hotter, severe weather conditions. Future testing should see the materials tested across a variety of ambient condition, including those in which bushfires thrive.

Ember Fuel Type

The wood chips used to create the embers in this test are not necessarily typical to the forest floor dead litter found in heavily wooded areas. Dead litter found in nature may be of greatly varied shape, density and oil and chemical composition. This means that any test pieces successfully tested against standard garden wood chips may fail against naturally found forest floor dead litter embers.

Ember Shower Simulator Settings

During this test the ESS remained in one constant state, always producing the same constant wind flow. While the wind flow produced was not scientifically assessed, observation of the embers showed the flow in the wind tunnel to be largely laminar, with the wind flow becoming increasingly turbulent as it exited the ESS outlet and approached the test piece. Future testing could incorporate vanes into the wind tunnel to intentionally incite turbulent flow and vortices, which may more accurately represent the turbulent and unpredictable wind flows in and around houses.

6 – Conclusion

The project objective was to analyse the current research into preventing ember attack and postulate alternative methods and materials which could be implemented instead. A comprehensive review of the current literature showed there were many studies on the effectiveness of the currently available and regulated designs, that being metallic screens. There were two areas with little to no research, alternative materials to use as screens and testing the current screens under a wider range of fuel sources to assess suitability in all areas. As an answer to this research gap, this project focused on studying flexible materials to use as ember shields, mainly a fire proof foam which had been successfully tested in other fire applications.

Like most foams, the fire proof foam could be easily ripped and deformed and as such would not survive long as a permanently installed ember screen option. It was decided to pair the foam with a supporting mesh material which would allow the foam shield to be deployed and used regularly without suffering damage. This meant the mesh material must also be fire proof. Two materials were chosen for testing as potential mesh supports, a standard shade cloth and standard outdoor canvas, typically used for outdoor roller blinds.

During the many rounds of testing, the foam has showed great resistance to burning embers. Tests conducted at other organisations have shown the foam wont burn and the testing during this project has shown the foam is highly resistant to melting too. When subjected to a continuous ember shower the foam only suffered mild damage when placed in the horizontal position, and no damage at all when tested vertically and at an angle. This shows the foam has excellent potential for further testing in this field.

The supportive mesh materials suffered varying levels of damage which will preclude them from further testing without substantial alteration. The shade cloth suffered catastrophic damage even when treated with two types of fire retardant spray designed for synthetic materials, thereby definitively eliminating it from future consideration. The canvas fared much better, suffering only a fraction of the damage taken by the shade cloth but for this to be considered for further testing a more permanent method of fire proofing will be required, as the fire proofing sprays used in this study were both water soluble, meaning the spray would need multiple and continued application to be effective.

This study has shown that the fire proof foam performs remarkably well for a foam, and should be considered for future testing against ember attack. If possible this foam is a prime candidate for further chemical alteration, possibly improving the mechanical capabilities such as elasticity and durability, or even improving its ability to withstand the ember heat, and undergo less or no melting. Also, if further testing is conducted the ember fuel source should be more thoroughly evaluated. This testing was conducted with completely dried solid timber chips, following a mostly regular size and weight distribution. As these wood chips burned down the embers they created were very similarly sized, with very little variation in shape. The foam was not tested against leaves and bark pieces of irregular size and chemical composition. It’s possible that further testing may show the foam is more susceptible to burning leaves which still contain eucalyptus oil, and burn longer and hotter than a small wood chip.

It is possible to continue research into alternative ember screen materials by extending the results from this study into future testing to study non-metallic materials which could be used to protect dwellings against ember attack.

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8 - Appendices

Appendix A – Project Specification

ENG4111 – Research Project – Part 1

Project Specification

For: Daniel Bellert

Title: Use of metal screens to defend properties during a bushfire

Major: Mechanical

Supervisor: Dr Ahmad Sharifian-Barforoush

Enrollment: ENG4111 – ONL S1, 2023

ENG4112 – ONL S2, 2023

Project Aim: To investigate new designs for ember screens by observing the performance of current, Australian Standard ember screens in the UniSQ ember simulator. The ultimate aim is to present new designs ready for prototyping and testing.

Programme: Version 1, 15th March, 2023

1- Bushfire research – Understanding the Problem:
  - Fire types, difference in bushfires by region and vegetation type / species
  - Weather patterns and environmental conditions during peak bushfire season
  - Potential differences in ember types with different vegetation species.

2- Mesh / Materials research – Understanding the Current Solution:
  - Current materials and manufacturing processes used for screens
  - Testing and research already undertaken on current screens.
  - Assess current Australian standards for suitability. Still relevant?

3- Ember Simulator – Understanding the Test Apparatus:
  - Inspect and understand testing procedure. Review prior testing conducted using this apparatus. Assess if/how apparatus can be used to provide a wider data set for a potentially more in-depth analysis.

4- Testing – Current Screen Types
  - Are current Australian Standards sufficient? Are current screen types sufficient?
  - Test screens under various conditions, find limitations and faults (if present) in current screen design.
  - Assess how current screens are installed. Investigate possible new ways of using or installing the screens to increase effectiveness.

5- Analysis – Finding improvement on current designs:
  - Find areas where the design and manufacturing of current designs can be improved.
  - Suggest new, improved designs including new mesh weaves and alternate materials or material processing.
  - Investigate potential costing for new designs to assess viability of further design.

If time and resources permit:

6- Modelling – Starting a new design:

- Undertake CFD modelling as preliminary testing on potential new weave designs. Create CFD modelling on previous design and compare results.

7- Prototype – Testing a new design in the Ember Simulator:
   - If possible, manufacture small quantities of a new mesh for testing in the simulator. It's preferred that multiple designs could be tested simultaneously for expediency.

Appendix B – Hot Work Permit

UNIVERSITY OF SOUTHERN QUEENSLAND

HOT WORK PERMIT

This Permit is to be used for any hot work performed outside a designated hot work area which could generate flames, heat or sparks including (but not limited to) welding, brazing, flame cutting or grinding.

BEFORE YOU START—CAN HOT WORK BE AVOIDED? IS THERE A SAFER WAY TO DO THE WORK?

1. DETAILS

Project/work order no.:

Fire ban check: There is no fire ban in active ☒

Fire Danger rating: Low-moderate ☒ High ☐ Very high ☐ Severe ☐ Extreme ☐ Catastrophic ☐

Name of person doing hot work: DANIEL BELLERT / AHMAD SHARIFIAN-BARFOROUSH

Work area/location: TOOWOOMBA CAMPUS - P1

Description of works: USE OF EMBER SHOWER SIMULATOR.

Hot work Tools to be used: Angle Grinder ☐ Oxy Acetylene ☐ Electric welder ☐ Other ☒

Additional Permits required: Working at height ☐ Confined spaces ☐ Electrical work ☐ Excavation/Penetration ☐ Hot Materials/Gases ☐

Permit Validity: Start: Date: 20/08/23 Time: 09:00 Finish: Date: 31/10/23 Time: 17:00

2. CONTROLS — all controls must be either in place or not applicable

Mandatory controls: Competent Personnel ☒ RMP & SOP ☒ Equipment Inspections ☐ PPE ☒ VRD (similar) on Elec. Welders ☐ Flashback arrestors on oxy. ☐ Guards and handles on Grinder ☐ Grinders with Deadman switch ☐

Other Controls	Yes	NA
Equipment:		
Inspected available sprinklers, hose streams and extinguishers and they are in service/operable	✓	
Inspected hot work equipment and it is fit for use	✓	
Requirements within 15m of work:		
All flammable liquids, dust (where practicable), lint and oily deposits have been removed	✓	
If applicable, area has been tested and is not an explosive atmosphere	✓	
Area is well ventilated/has mechanical ventilation	✓	
Floors have been swept/washed clean		✓
If applicable, combustible floors have been wet down/covered in fire-resistant sheets/wet sand		✓
Other combustibles (e.g., vegetation, pallets, etc.) have been removed		✓
Other combustibles have been protected with welding pads/blankets/fire-resistant tarpaulins		✓
If applicable, wall and floor openings covered		✓

Other Controls	Yes	NA
Welding pads, blankets and curtains installed under and around work		✓
If applicable ducts and conveyors have been shut down/protected		✓
If work is on walls, ceilings, or roofs:		
Construction is non-combustible and without combustible covering or insulation		✓
Combustibles on other side of walls, ceilings or roofs have been moved away		✓
If work is on enclosed equipment:		✓
Enclosed equipment cleaned of all combustibles		✓
Containers purged of flammable liquids/vapours		✓
Pressurised vessels, piping and equipment removed from service, isolated, and vented		✓
If work is outside:	✓	
Work is enclosed or not exposed to wind	✓	

3. FIRE RISK —assess the following items and tick if the conditions exist

Item	Yes
Non-combustible floor (e.g., metal, cement) on ground level or fully sealed floor to lower level	✓
No combustible materials or those within 15m are controlled using fire blankets, appropriate screens	✓
No walls or those within 15m are non-combustible or controlled i.e., fire resistant screens are used to mitigate risk	✓
Area enclosed or otherwise no wind	✓
Low heat task (e.g., soldering, grinding)	✓
Highly frequented or camera monitored area	✓

4. FIRE WATCH AND INSPECTION REQUIREMENTS—are based on fire risk results in Section 3 above

All 6 tasks ticked "Yes"	4 or 5 items ticked "Yes"	less than 4 items ticked "Yes"
Low No firewatch or inspection required after.	Medium No Fire watch. Inspect every 30min for 3hrs after work completed or until work is under 50°C	High or Extreme Independent fire watch required during work, continuing for 1 hour after work completion. Inspect every 30mins for 3 hours thereafter.

5. SIGNATURE - PERMIT USER

Permit User Name: DANIEL BELLERT Position: ONLINE FINAL YEAR STUDENT Signature: [redacted] Date: 20/08/23 Time: 09:00

6. AUTHORISATION FOR HOT WORK TO START

I have examined the location. The Fire Risk Category in Section 3 is correct; the Controls ticked in Section 2 have been put in place. If required by the Fire Risk Category, a fire watch and inspection process has been put in place.

Permit Authoriser Name: Ahmad Sharifian Position: Academic staff Signature: [redacted] Date: 21/8/23 Time: 19.00

7. PERMIT CLOSURE —tick 3 which fire risk category inspection applies for this Permit

Medium Risk Fire Category
The work was inspected over 3 hours or until under 50°C
The Permit is closed, and the area is fire safe.

High or Extreme Fire Risk Category Only
The work area was watched for 1 hour and inspected over 3 hours thereafter.
The Permit is closed, and the area is fire safe.

FIRE WATCH SIGN OFF (if provided)—Work area was monitored during work as indicated by the requirement above and all adjacent areas to which sparks, and heat might have spread were inspected at the end of the work and were found fire safe. The Permit is now closed, and the area is fire safe.

Fire Watch Name: Position: Signature: Date Closed: Time Closed:

Appendix C - Risk Management Plan

NUMBER	RISK DESCRIPTION	TREND	CURRENT	RESIDUAL
2998	Using the Ember Shower Simulator (ESS) to test effect of embers on Treated Foam and Polymer Based Materials		Low	Low

DOCUMENTS REFERENCED

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
Daniel Bellert	26/08/2023	27/08/2023	27/08/2024

RISK FACTOR(S)	EXISTING CONTROL(S)	PROPOSED CONTROL(S)	OWNER	DUE DATE
Possible burns from skin contact with the fire - when starting the fire - when maintaining the fire - when extinguishing the fire	**Control:** Use correct protective clothing and equipment - gloves - safety glasses - long sleeve shirt & long pants - enclosed, impervious shoes **Control:** Fire to be started in the steel firebox. Fire to be constrained to the steel firebox. Firebox to remain closed and latched while fan is on. **Control:** Only a limited amount of woodchips will be used at any one time, to limit the size of the fire. The amount of woodchip to be used for extended testing sessions will be derived during the first session, in agreement with Ahmad and the accompanying technician/s.			

	Control: Operator to use steel tools such as tongs, rather than hands when tending to the burning wood chips.	
Errant or stray embers at the exit of the wind tunnel. - Possibly travel on the wind and be a source of ignition elsewhere. - Possibly come into contact with a person, subjecting them to burns.	**Control:** Use correct protective clothing and equipment - gloves - safety glasses - long sleeve shirt & long pants - enclosed, impervious shoes **Control:** The apparatus will be placed in an area isolated from other people, buildings and ignitable material such as buildings. **Control:** The operator will be stationed in a designated safe area during operation. The safe area will be away from the wind tunnel exit, thereby eliminating the possibility of being struck by errant embers. **Control:** The test material sits at a distance of approximately 500mm – 700mm from the wind tunnel outlet. Approximately 500mm behind the test screen is a solid, impervious non-flammable barrier created by joining corrugated steel roofing sheets together. It is 2800mm high and 1500mm wide. It will prevent errant embers from blowing past, or through the screen and being carried away on the wind. **Control:** Sufficient fire extinguishers to be present at testing facility. Fire extinguishers to be of the right type. (burning wood) Hose / Fire hose is present and functional. This allows the	

	fire to be extinguished quickly and effectively. **Control:** Works to be carried out with a spotter to monitor the embers as they exit the ESS. Spotter to use hose or buckets of water to extinguish errant firebrands.	
Heat created by burning wood chips inside the firebox. (in excess of 100 degrees Celsius) - Will provide radiation heat to people nearby - Could cause burns to operator if contact is made with skin.	**Control:** Use correct protective clothing and equipment - gloves - safety glasses - long sleeve shirt & long pants - enclosed, impervious shoes **Control:** Fire is contained within the firebox. Remain at a safe distance from the firebox when not attending to the burning wood chips inside. Operators, technicians and supervisor to remain a minimum of three meters from the firebox during testing.	
Existence of smoke - irritant to eyes - irritant to lungs	**Control:** The apparatus is to be used in an outdoor environment, providing complete ventilation. Any smoke generated will disperse. Operators will not be required to work with smoke in an enclosed space. **Control:** Use correct protective clothing and equipment - eye protection - appropriate level masks to be worn over nose and mouth of operators. **Control:** Mechanism which causes greater amounts of smoke is to be eliminated. Wood chips being burned	

	will be dried in a commercial oven prior to burning. This will greatly reduce the amount of smoke created.	
Possible ignition of testing materials - Fire Guard Foam may not withstand testing as expected - it may ignite - Shade Cloth may not withstand testing as expected - it may ignite - Outdoor roller blind material may not withstand testing as expected - it may ignite. If these materials ignite, they can: - melt, coming into contact with operator or ground - send out small burning embers - create noxious fumes	**Control:** Use correct protective clothing and equipment - gloves - safety glasses - long sleeve shirt & long pants - enclosed, impervious shoes **Control:** Extra person in attendance to act as spotter. They can monitor any burning embers and extinguish them quickly. **Control:** Use correct fire extinguisher to extinguish the burning material: These types will work: - Red stripe - Water - White stripe - Dry Chemical Powder ABE - Blue stripe - Foam **Control:** The testing will be conducted on a concrete slab, in an outdoor area which is: - Extremely well ventilated - Easily cleaned from burnt or melted materials - Undamaged by burnt or melted materials - Inflammable	
Possible strain or injury to operator when moving the apparatus. - Apparatus is designed to be mobile, with 4" castor wheels welded to the bottom of the supporting framework. - Apparatus is to be wheeled outside before use. - Apparatus is long, heavy and cumbersome	**Control:** Two or more people must be in attendance before moving the apparatus outside. **Control:** Operator must ensure the pathway is clear of obstructions and free of debris which could possible inhibit the rolling wheels.	

	Control: Pre-checks to be completed on the apparatus before moving. - Ensure all sections are attached securely. - Ensure all wheels are free to rotate properly. **Control:** All people in contact with the apparatus are to use appropriate protective clothing to prevent incidental injuries such as cuts or bruises. - gloves - safety glasses - long sleeve shirt & long pants - enclosed, impervious shoes	
Possible electrocution from 240V source. - Drum fan to be connected to 240V in order to operate	**Control:** Ensure the fan has been safety tested recently. - Check the attached tag. - Visually inspect the fan for faults in construction and breaks in the insulation on the wiring. - Ensure the fan is connected to a circuit with a safety switch installed.	
The apparatus will be used in an outside location. Operators may suffer from: - Sunburn - Dehydration - Heat stroke	**Control:** Use correct protective clothing and equipment - gloves - long sleeve shirt & long pants - enclosed, impervious shoes Additional PPE: - Sunscreen - wide brimmed hat **Control:** - Ensure operator/s are consuming adequate water. - Limit the duration of the testing period to 2 hours. - Only conduct testing in acceptable weather conditions. No testing to be done during rain, extreme heat or extreme windy conditions. - Testing sessions to be concluded before hotter weather begins.	

	Control: Operators to remain in shaded areas when possible. - between testing runs - during any delays or waiting periods.	

Appendix D – Fire Retardant Spray Details

Fire Retardant Spray 1:

Name:	Fire Defender Multi-purpose Fire Retardant
Price:	AUD $36.00
Size:	750 ml
Supplier:	Fire Defender, Clontarf, QLD Australia
Website:	https://www.firedefender.com.au

Fire Retardant Spray 2:

Name:	Fire Guard Flame Retardant
Price:	AUD $33.45 (amazon.com.au)
Size:	650 ml
Supplier:	Shield Industries
Website:	https://shieldindustries.com

Appendix E – Data Sets: Ember Burns in Horizontal Foam Test Pieces

FOAM - 5mm - HORIZONTAL TEST						
	<1mm deep	1-2mm deep	2-3mm deep	3-4mm deep	4-5mm deep	>5mm deep
<5	37	1	1	0	0	0
5 - 10	29	5	0	0	0	0
10 - 15	19	15	3	0	0	0
15 - 20	12	17	7	2	0	0
20 - 25	5	13	6	2	0	1
25 - 30	2	8	6	3	1	2
30 - 35	1	8	5	2	2	2
35 - 40	1	4	4	3	0	3
40 - 45	0	2	0	2	0	2
45 - 50	0	1	0	1	1	1
50 - 55	0	0	0	0	0	0
55 - 60	0	0	1	0	0	1
60 - 65	0	0	0	1	1	0
65 - 70	0	0	0	0	0	0
70 - 75	0	0	0	0	1	1
75 - 80	0	0	0	0	0	0
80 - 85	0	0	1	0	0	1
85 - 90	0	0	0	0	0	1
90 - 95	0	0	0	0	0	0
95 - 100	0	0	0	0	0	0
Total	106	74	34	16	6	15

Figure AE1 – Burn mark counts in 5mm thick foam test piece. Area of burn mark (mm^2) vs depth (mm).

FOAM - 10mm - HORIZONTAL TEST											
	<1mm deep	1-2mm deep	2-3mm deep	3-4mm deep	4-5mm deep	5-6mm deep	6-7mm deep	7-8mm deep	8-9mm deep	9-10mm deep	>10mm deep
<5	39	5	0	0	0	0	0	0	0	0	0
5 - 10	34	17	3	0	0	0	0	0	0	0	0
10 - 15	3	19	6	3	1	0	0	0	0	0	0
15 - 20	0	8	6	4	0	0	0	0	0	0	0
20 - 25	0	4	5	3	1	0	0	0	0	0	0
25 - 30	0	2	4	3	0	0	0	0	0	0	0
30 - 35	0	0	3	1	0	0	0	0	0	0	0
35 - 40	0	0	3	1	1	0	0	0	0	0	0
40 - 45	0	1	2	1	0	0	0	0	0	1	0
45 - 50	0	0	0	0	0	0	0	0	1	0	0
50 - 55	0	0	0	0	0	0	0	0	0	0	0
55 - 60	0	0	0	0	0	0	0	0	0	0	0
60 - 65	0	0	0	0	0	0	0	0	0	0	0
65 - 70	0	0	0	1	0	0	0	0	0	0	0
70 - 75	0	0	0	0	0	0	0	0	0	0	0
75 - 80	0	0	0	0	0	0	0	0	0	0	0
80 - 85	0	0	0	0	0	0	0	0	0	0	0
85 - 90	0	0	0	0	1	0	0	0	0	0	0
90 - 95	0	0	1	0	1	0	0	0	0	0	0
95 - 100mm	0	0	0	0	0	0	0	0	0	0	0
>100mm	0	0	0	0	0	0	0	0	0	0	0
Total	56	33	17	5	0	0	0	1	1	0	0

Figure AE2 – Burn mark counts in 10mm thick foam test piece. Area of burn mark (mm^2) vs depth (mm).

FOAM - 20mm - HORIZONTAL TEST

	<1mm deep	1-2mm deep	2-3mm deep	3-4mm deep	4-5mm deep	5-6mm deep	6-7mm deep	7-8mm deep	8-9mm deep	9-10mm deep	>10mm deep
<5	32	6	2	0	0	0	0	0	0	0	0
5 - 10	10	18	3	0	0	0	0	0	0	0	0
10 - 15	2	13	7	0	0	0	0	0	0	0	0
15 - 20	1	3	7	0	0	0	0	0	0	0	0
20 - 25	0	2	2	0	0	0	0	0	0	0	0
25 - 30	0	2	4	2	0	0	0	0	0	0	0
30 - 35	0	0	0	0	0	0	0	0	0	0	0
35 - 40	0	0	1	2	1	0	0	0	0	0	0
40 - 45	0	0	0	4	0	0	0	0	0	0	0
45 - 50	0	0	0	1	0	0	0	0	0	0	0
50 - 55	0	0	0	0	0	0	0	0	0	0	0
55 - 60	0	0	0	1	0	0	0	0	0	0	0
60 - 65	0	1	0	1	0	0	0	0	0	0	0
65 - 70	0	0	0	0	0	0	0	0	0	0	0
70 - 75	0	0	0	0	0	0	0	0	0	0	0
75 - 80	0	0	0	0	1	0	0	1	0	0	0
80 - 85	0	0	0	0	1	0	0	0	0	0	0
85 - 90	0	0	0	0	0	0	0	0	1	0	0
90 - 95	0	0	0	0	0	0	0	0	0	0	0
95 - 100mm	0	0	0	0	0	0	0	0	0	0	0
>100mm	0	0	0	0	0	0	0	0	0	0	0
Total	45	45	26	11	3	0	0	1	1	0	0

Figure AE3 – Burn mark counts in 20mm thick foam test piece. Area of burn mark (mm^2) vs depth (mm).

Appendix E – Test Material Photos

Figure AF1 – Shade Cloth untreated.

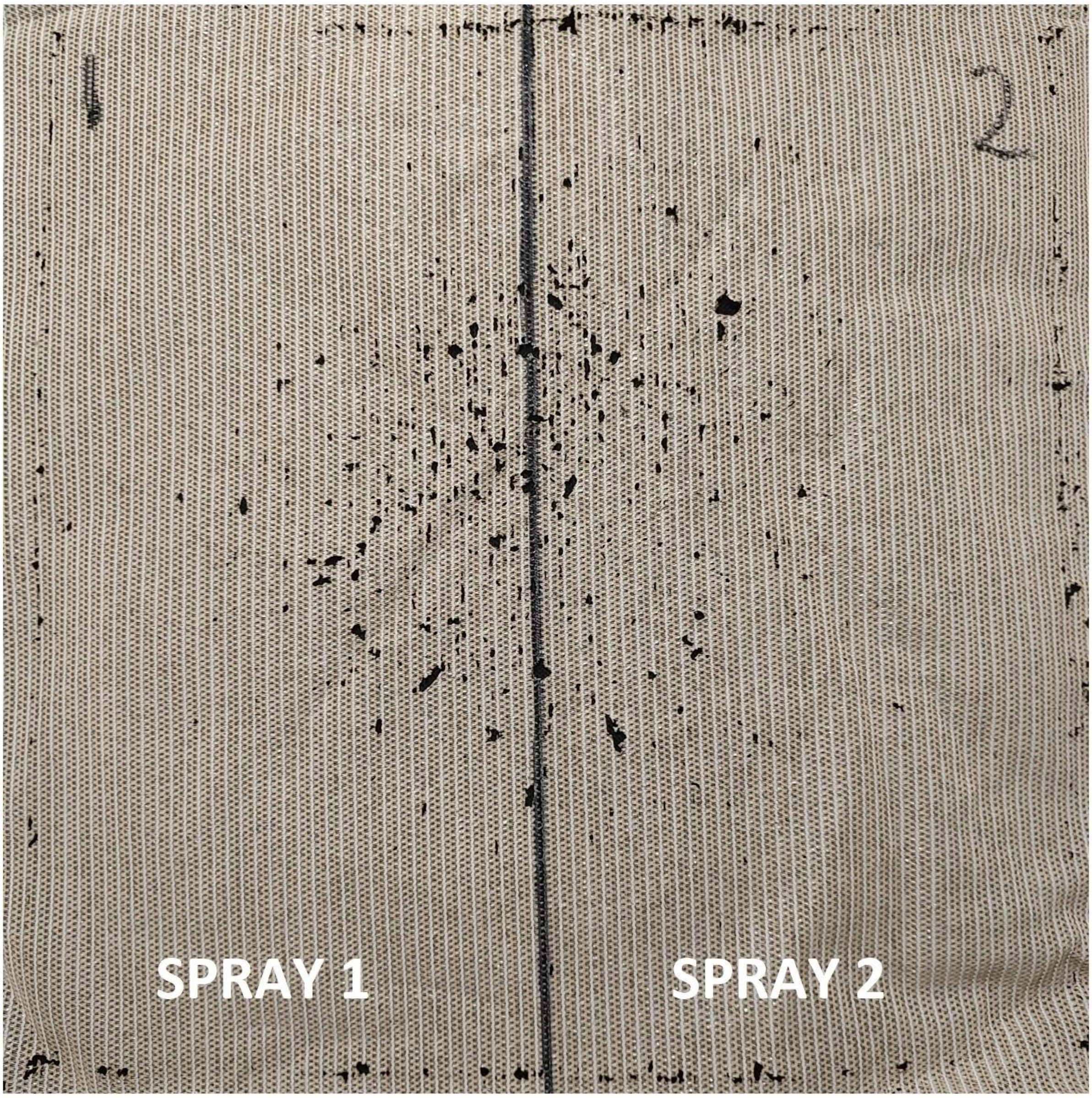

Figure AF2 – Shade Cloth Treated with Spray 1 (LHS) and Spray 2 (RHS)

Figure AF3 – Outdoor Roller Blind Canvas - Untreated

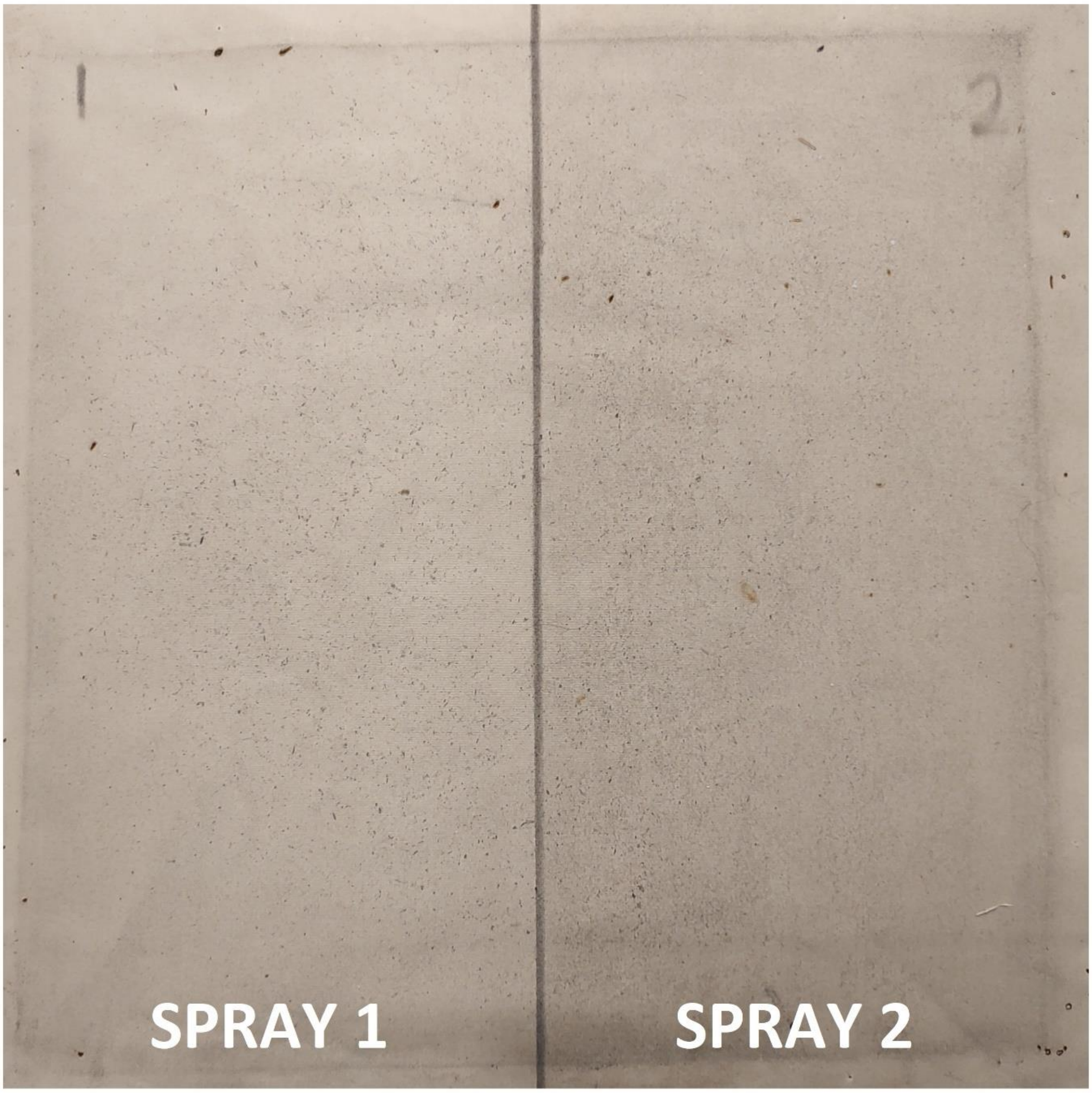

Figure AF4 – Outdoor Roller Blind Canvas – Treated with Spray 1 (LHS) and Spray 2 (RHS)