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Study on the burning behaviour of green walls with reduced moisture content

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International Master of Science in Fire Safety Engineering

Declaration

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Read and approved,

Matthew Newcomen

May 11th, 2022.

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1. Abstract

Modern green wall systems typically consist of plants held on to the side of a building by a series of plastic planters. The fire safety risks posed by a green wall in the event that they are dryer than expected are not fully understood at this time. To date, most of the fire performance testing has been conducted on properly watered green walls. An experimental program was carried out to investigate the effect that a lack of moisture has on a green wall module's ability to burn. The first part of the program involved drying out and burning individual leaves and later entire plants, to form a better understanding of how a moisture affects plant flammability. The final stage of the program involved drying out a genuine module in an oven, attaching it to an apparatus designed to replicate a professional installation, and then exposing it to a pilot flame. This test was performed with four modules with different drying times. The plant canopy became partially flammable after 4.2% of the mass was lost due to drying, and fully flammable after 16.7% was lost. The soil was also observed to smoulder during these tests. However, neither the canopy fire or soil smouldering were able to ignite the plastic on their own. A direct impingement of the pilot flame on the lower plastic module failed to spread upward, because the melted plastic dripped away too quickly. However, an identical fire started at the top of the module could spread downward, but the size of the resulting fire was dependant on the soil moisture. Also, the fire was able to puncture the back side of the module and instigate a fire in the cavity between the module and the plaster board wall of the apparatus.

2. Introduction & Objectives

Green walls, sometimes referred to as living walls or vertical gardens, have existed in some form for centuries. The fabled Hanging Gardens of Babylon continue to capture public imagination, window box planters have been in use since ancient Rome, and the walls of prestigious universities are often adorned with ivy. However, the modern concept of a green wall, complete with an irrigation system and cellular plant compartments, was first developed in the mid-20th century. They have seen a surge in popularity worldwide in recent year, due to their aesthetic appearance and environmental benefits, leading to the establishment of an industry that provides standardized products that are sold worldwide. However, the use of living material in the building industry presents unique fire safety challenges, which need to be thoroughly understood.

2.1 Fire Risks

The emergence of these new green wall systems has also prompted questions about their fire risks. As long as the green wall is adequately watered and maintained, the general consensus is that they should be perfectly safe (Barnett, 2021). However, the expected service life of a green wall could be decades, so it is important to understand these properties as the current generation systems begin to age. In order to stay alive, they require a regular maintenance schedule that is comparable to any other landscaping installation. This stands in contrast with most other building components, which are serviced much less frequently. In the event that green wall maintenance is allowed to lapse, the plants could dry out significantly, and fire safety of the building could potentially be compromised. (Knez, 2014) There have been incidents of green wall fires already, and reports suggest that they can fuel a rapid spread of fire across their surface, further fuelling calls for increased study and regulation. (McNeilage, 2012) However, their fire safety properties in the event of a lack of irrigation have not been thoroughly explored. (Warringtonfire, 2013)

Some fire risk testing has been carried out on vegetation, for the explicit purpose of furthering the understanding of green walls. (Dahanayake & Chow, 2018) Not surprisingly, the lower moisture plants had lower ignition times and higher heat release rates. Reduced scale studies of green wall fires in compartments show that they are not prone to burn when fully watered. However, the fire risk increases as the plants dry out. The propagation of this fire was noted to be particularly fast in the vertical axis, but slow on the horizontal axis. (Dahanayake & Yang, 2020) To date, there has not been a comprehensive study into the fire risk of a dry exterior green wall facade, and a universal fire test scenario for such a construction has not yet been developed. (Chow, Han, & Dahanayake, 2018)

Figure 1: Decaying Green Wall (Pearman, 2021)

The four primary types of organic fuel in a green wall are listed below. The nomenclature and related information is mostly borrowed from wildfire literature, which is a more active field of research. (USDA, n.d.)

- Ground fuels: organic material stored in the soil such as peat, roots, soil, or other decaying plant matter. They can ignite and smolder for a long time. Ammonium nitrate fertilizer can exacerbate this issue. Additionally, their thermal properties are heavily dependent on moisture content.

- Surface fuels: plant debris that have built up on the surface. These can ignite from discarded cigarettes, embers from barbeques, etc. This is usually only an issue when vertical green walls also feature a horizontal surface, or if it is located close to the ground.

- Canopy fuels: Sometimes referred to as aerial fuels, these are any fuel located above the surface of the well. In this case, they are typically plant leaves and branches. If they are dry enough, they can rapidly burn.

- Lateral fuels: vines or long plants. Due to the vertical nature of the wall, long plants are sometimes selected. If ignited, they could allow flame to spread upward easily. Not all researchers consider this to be a distinct fuel category. However, because green walls cover large vertical spaces, it is important to draw the distinction.

The green wall façade material itself is also a potential fuel source. The plants need to be held in place by a series of inorganic plant containers, which are often made out of combustible material such as plastic. (Champ, 2019) If a plant fire is able to ignite these containers, the overall size of the fire would increase dramatically. However, there are several different types of green wall containers, which utilize varying types of fuel.

A green wall system may also be susceptible to some of the same fire spread mechanisms as regular facades. If it is made out of plastic, the fire may be able to rapidly spread downward. When plastic catches fire, it can melt and produce droplets which flow down the surface, potentially causing combustion at a lower evaluation. (Ruo-wen Zong, 2018)

Additionally, if there is a gap between the green wall system and the building wall, there is a risk that a unique type of fire could form. If a fire is able to spread to this area, the façade and building wall can keep the plume trapped in this 'cavity', effectively creating a chimney, where one of the walls is also flammable. When air entrainment into a plume is restricted, the amount of oxygen available to produce combustion is reduced, and the temperature of the plume will also decrease much more slowly. Therefore, the hot gases will remain un-combusted until they encounter more oxygen. This can cause the length of a flame to increase dramatically, and therefore propagate further. (Drysdale, 2011) The potential for a gap between two surfaces to act as a chimney is a known phenomenon; it is commonly referred to as a ventilated cavity fire. Although understanding of the subject remains incomplete, there is no dispute that it poses significant risk to building safety. Existing research suggests that a ventilated cavity fire can increase flame height by ten fold over a comparable single wall fire. (Colwell, 2013) The heat flux from a cavity fire has been proven to be able to ignite combustible material at a much higher elevation than a single wall fire. Also, a more narrow the gap will typically produce a higher the heat flux, until it becomes too narrow and chokes out the flame. (Livkiss, 2018) Any evidence of this happening in a green wall system would be cause for concern.

2.2 Green Wall Selection

The primary objective of this project is to determine the effect that a lack of moisture content of a green wall has on its flammability. In order to do this, there were two important decisions to be made: the type of green wall, and the plant species used in it.

Broadly speaking, there are three ways to build a modern green wall, listed below. (Warringtonfire, 2013)

1. Climbing plant wall. Accomplished by using plants such as vines and ivy, which grow directly on a wall or external trellis. These can be

rooted in both the ground and elevated soil planters. They do not necessarily need an irrigation system to survive, although many have them. The benefit is they are able to use non-flammable materials to form the trellis, such as steel cable, and they are not subject to erosion. The downside is there are limited varieties of plants to choose from, and the continuous vertical plants make fire breaks difficult to implement.

Figure 2: Climbing Plant Wall (Jakob Webnet , 2021)

2. Hydroponic wall. Accomplished using an artificial growing medium instead of soil. Examples include plastic mesh, mineral wool, and fabric. They instead require an irrigation system with nutrients mixed into the water to keep the plants alive. The benefit is they are not subject to erosion, and a wide variety of plants can be used. The downside is the growing medium could have fire properties that are worse than standard soil, and it can be costly to maintain the constant supply of nutrients needed by the plants.

Figure 3: Hydroponic Wall (Willerby Landscapes Ltd)

3. Modular Green Walls. Accomplished using prefabricated modular panels with cells for the individual plants and soil. They are usually made out of a lightweight plastic or fabric, and are fixed to the wall or frame of the structure. An irrigation system is usually required, but the nutrients can be added to the soil directly, if desired. The benefit of this system is they have a considerable amount of soil, which can act as thermal ballast in a fire scenario if it is sufficiently watered, and they can incorporate a wide variety of plants. The downside is the module material can be flammable, the soil is at risk of erosion due to its vertical orientation, and the panels can be quite heavy.

Figure 4: Modular Green Wall Panel (RR Landscape solutions Ltd)

From this list, the modular green wall system was chosen for this study. The rational was that they have most of the aforementioned fuel sources represented in the system. They are also soil based, so there would be less variability from one type of system to another. Both of these factors increase the usefulness of this research by increasing its applicability to other systems. The hydroponic systems have much more variable substrates, which are often proprietary material, so testing with one of them would not be applicable to another. The climbing plant wall does not have a growing medium, apart from at its base, so subjecting it to a fire test would not have yielded results that are applicable to other systems.

The modular wall system also has the benefit of being relatively cheap and simple to construct and install by a non-professional. There are a number of direct to consumer products on the market today for homeowners to add to their own domiciles. Fortunately, we did not have to build our own, since ANS Global generously agreed to supply us with several genuine green wall panels, complete with plants, to use for this project.

The second important decision to be made was the selection of plants used in the wall panels. For commercial installations, the selection is based on the climate, local ecology, and anticipated sunlight based on the wall's location. Generally, native plant species are more desirable, since they are more likely to flower and benefit the local ecosystem. (Mcintyre, 2021) In the case of this experiment, it was important to be able to source some of the plants locally before receiving the actual panels, so their fire characteristics could be better understood before the full scale testing started. In order to do this, the list of available plants from ANS Global was cross referenced with a local plant shop, to ensure that a ready supply would be available during the research phase. Unfortunately, this project was conducted during the winter of 2022, when most of the local flowering plants have not yet started to bloom. Therefore, a higher than usual amount of evergreen plants was used. The species used were Pachysandra terminalis, Thymus vulgaris, Armeria maritima, and Carex oshimensis, since they were readily available at low cost from a local shop.

2.3 Code

At present, the green walls in the United Kingdom are subject to the regulation on the reaction to fire performance of external surface of walls in Approved Document B. (HM Government, 2020) Depending on the height and boundary distance of the building, and the location of the wall on the building, the minimum required classification for a none residential building is either B-s3, d2 or C-s3, d2 (European class). This classification is based on a given product's ability to resist fire in accordance with BS EN 13501-1: 2002. The possible classifications are A1, A2, B, C, D, E, and F, with A1 being the best and F being the worst. In order to achieve a C rating or better, the product must undergo the BS EN 13823 Single Burning Item test (SBI). This test involves constructing a corner area out of the wall material under an extraction hood and exposing it to a fire source for a prolonged period. See Figure 5 for a visualization.

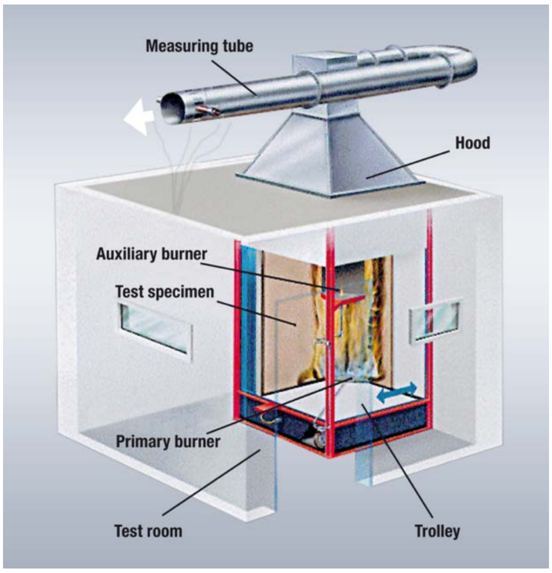

Figure 5: SBI Test (Störkmann, 2012)

The SBI test is a small scale test, meant to accurately replicate the results of an actual building fire at a lower cost. The total area of wall being tested is only 2.25 m^2, which is much smaller than the wall of even a single storey building. Additionally, when testing a green wall, the manufacturer is permitted to use fully living plants, which will have a relatively high moisture content, both in the canopy and soil. This could act as a thermal ballast and slow the spread of fire. Therefore, this testing scenario assumes that the green walls are adequately watered and maintained, which is not necessarily the case.

Figure 6: Green Wall SBI Test (Dale, 2021)

This issue has occurred to the British authorities. They have conducted cone calorimetry tests on dried samples of growing medium to determine the risk of ignition. Since no such ignition occurred, they concluded that it was extremely unlikely that the medium would contribute to a fire, even when fully dry. (Warringtonfire, 2013) At the time of publication of the most recent guidance on green walls, there had not been any systems capable of passing the SBI test, so the issue of plant/soil moisture as a thermal ballast has not yet been resolved. This also means that green wall systems are limited to use on buildings less than 18m tall, and with more than 1m of boundary distance, since there are no minimum classifications for building materials.

There are other issues with testing a green wall system in the SBI framework, as well. The BS EN 13823 test requires that the specimen be conditioned to a temperature of 23±2 °C and a relative humidity of 50±5%, either for a fixed period of time or until it achieves a stable mass. Because the specimen is a living plant, a constant mass is essentially impossible to achieve. Also, a steady supply of water is needed to keep the plants alive, which would alter the relative humidity. Therefore, it is not possible to conduct a valid SBI test under the current rules. However, several manufactures have chosen to conduct the test purely for demonstrative purposes. (Dale, 2021) To my knowledge, none of them have attempted the test using plants that have been intentionally left dry, leaving this a relatively unexplored area.

2.4 Drying Method

The limited amount of time available for this project meant that it was not practical to have the plants dry out naturally. Instead, we had to find a way to accelerate the drying process without altering their physical or chemical properties. A more suitable alternative would be using a thermal chamber, or oven, in the lab. However, the drying temperature still needed to be determined. There is a variety of literature on this subject, mostly from wildfire research. The temperatures used typically range between 60 °C and 105 °C. (Matthews, 2010) Plant fuels will eventually reach an equilibrium moisture content (EMC) when exposed to a constant temperature and humidity. Higher temperature and lower humidity will cause more water to evaporate from the plants. However, plant fuels also contain volatile organic compounds (VOC) that are lost at elevated temperatures as well. They are transported to the surface by the evaporating water and then lost to diffusion. (Matthews, 2010) This presents a predicament for the drying process. A higher temperature will result in more complete evaporation of water but more VOC lost, and a lower temperature will maintain more VOC and water. It is impossible to fully remove the water content without also losing some organic plant mass. Therefore, plant samples dried at one temperature are not necessarily comparable to those dried at others.

The goal of this drying process is to replicate the natural process of a plant drying because it is not being watered, not to dry them out completely. Under normal temperature and humidity conditions in the United Kingdom, the EMC would not allow plants to lose the amount of moisture they would after 20 hours in an oven set to even 60 °C. Also, volatile organic compound vapours are flammable, so it is important that they be preserved within the plants. (Courty, 2010) For these reasons, 60 °C, the lowest temperature in the recommended range, was selected.

Another important decision was the drying temperature of the soil samples. This did not necessarily have to be the same as the plant drying temperature, since the soil was being dried out purely for analytical purposes, not for future testing (see section 3.2). However, because different drying temperatures do not necessarily yield comparable results, it was important to maintain a constant temperature between the two stages. Therefore, the decision was made to use 60 °C as the drying temperature for all plants and soil samples.

3. Methodology

The literature review described the risk of fire to a green wall, the types of green walls, and the specific type that will be used in this study. The following study will outline exactly how these characteristics will be studied. The plant species described in section 2.1 were all subjected to the three tests that are outlined below. All plants were kept in a nearby green house and watered regularly until it was time to test them.

3.1 Leaf Burning

Clippings of leaves were taken from each plant and individually weighed on an analytical balance. Each leaf was then placed on a tray in an oven set to 60 °C, and the time was recorded. After variable amounts of time, the leaf was removed from the oven, and it’s new mass was recorded, as well as the time of removal.

After being weighed, the leaf was placed in a clamp fixture so that the rest of the leaf was oriented below it. Then, the bottom tip of the leaf was exposed to a small flame from a hand held burner. The results of the exposure was recorded on video for further analysis. The video was then reviewed and the sample was placed into one of following two categories.

1. No ignition. There was no visible flame, but there may have been some smouldering.
2. Ignition. There was a visible flame, which may or may not have been able to fully consume the leaf

Category 2 is a fairly broad way to measure flammability, but given the inherent difficulty of studying a large number of such small samples, it was deemed to be a suitable method.

The objective of this portion of the project was to assess roughly how much moisture loss could occur before the leaf would become flammable. This information would be used later in the project to support the larger scale burning studies.

3.2 Plant Burning

The next portion of the project was to conduct burn studies on the entire plant. This was done by first weighing each plant on a lab scale, and placing it in an oven set to 60 °C. After a predetermined amount of time, the plant was removed from the oven and weighed again. Once weighed, a soil sample was taken from the plant and placed in an aluminium cannister with a known mass. This cannister was weighed on the analytical balance, and then placed back in the 60 °C oven. After at least 4 days in the oven, it was removed and placed back on the analytical balance. By subtracting the mass of the cannister from both values, and then subtracting the new mass from the original and then dividing by the original, the percentage of mass lost was determined. This is how the moisture content of the soil at the time of testing was determined.

Once the soil sample had been removed, the plant was reweighed, and then brought to the FPA. A sheet of gypsum plaster board, type A was pre-cut to fit the dimensions of the plant container, and then wrapped in aluminium foil. This was placed on top of the FPA specimen heaters, and a stack of plastic spacers were placed on the scale. The plant was then placed in the hole in the plaster board. This was done to simulate the "ground" that would normally surround the plant, and to prevent pyrolysis of the soil or plastic plant container.

Once the machine had been calibrated, the fire test was ready to commence. To provide a source of ignition, 5 lengths of cotton sting, each 20 cm long, were soaked in heptane, and then wrapped around the base of the plant canopy. This was ignited, and the results were recorded on video for further analysis. The FPA recorded the heat release rate, exhaust flow rate, and species concentration of O2, CO, and CO2. The software calculated heat release rate using two methods. The first is referred to as Janssens and used oxygen consumption by the fire to determine the amount of heat released (Janssens, 1991). The second, known as Brohez, was a method designed specifically for high soot flames (Brohez, 2000). Since these tests were not expected to produce a high levels of soot, only the Janssens method results are analysed.

It also recorded the mass of the plant, but the snug fit on the surrounding plaster board is expected to have interfered with this, so that value was not used in the results section. Instead, the final weight of the plant was taken using the lab scale once the experiment concluded. This process was repeated for a number of different plants. Additionally, a series of 5 'control' tests of just heptane soaked string were conducted in order to determine their contribution to the net HRR. Initially, the results of these tests was averaged and that values was subtracted from the HRR of the results of each plant. However, this created a number of tests with fully negative heat release rates, suggesting that the string was not always fully consumed during the test. The results of the control strings will be presented for reference, but this data will not be used in the presentation of the plant test data.

3.3 Module Burning

The final stage of the project was to conduct a fire test on the actual green wall modules. A testing stand was constructed to hold the modules upright as they normally would on a building installation. The mounting area had a back side made from plaster board, to replicate the building exterior that they would be installed on. The modules were held in place with two screws that passed through the mounting holes, and were attached directly to the rear plaster board. When installed, the module did not sit flush on the rear plaster board. There was a small gap created by the spacers located on the back of each module. Refer to Figure 7 for a diagram of the module that was used.

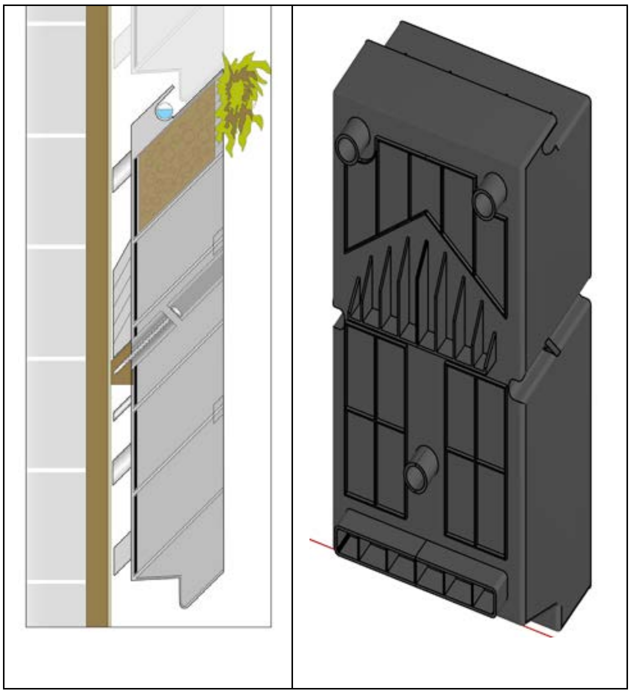

Figure 7: Module Installation Diagram (Mcintyre, 2021)

There were also elevated sections of plaster board on either side of and below the module, to replicate the other modules that would normally be installed around it. These were supported by a 2” thick ‘U’ shaped wooden collar that was mounted to the main plaster board. These smaller sections of plaster board were periodically scorched on the surface by the experiments, so they were replaced as needed.

Figure 8: Stand, Portrait View

Figure 9: Stand, Profile View

This stand was built on a frame of wooden 2” x 2” boards. The vertical boards were mounted to a different frame made of 8020. This frame sat on top of a load cell, in order to measure the mass loss of the module as it burned. The entire test was conducted under a large extraction hood, which captured the gases from the fire. These gases were then put through a gas analyser, which measured the O2, CO, and CO2 concentration. The data capture program used that data to calculate the heat release rate of the fire.

The green wall modules that we received did not have identical plant arrangements, which could affect the outcome of the study. Therefore, the arrangement was changed so that the bottom two cells of each module was identical, with a Pachysandra Terminalis on the left side and a Carex Oshimensis on the right, since they typically had the largest canopy. The plant arrangement in the other cells were not made uniform between modules.

Each module was weighed and then placed into the oven set to 60 °C. After a predetermined amount of time, it was removed and weighed again. After that, four samples of dirt were taken from the module, while making note of which cell each sample came from. These were placed in cannisters and underwent the same moisture calculation procedure described in section 3.2. After this, the module was reweighed.

The module was then mounted to the stand using screws. The flame source for this experiment was a lateral propane igniter with a series of eleven holes to distribute flame evenly across the bottom of the module. The propane flow was set to 0.04 g/s, which translates to a roughly 1.85 kW fire. (Drysdale, 2011) This is referred to as the pilot flame.

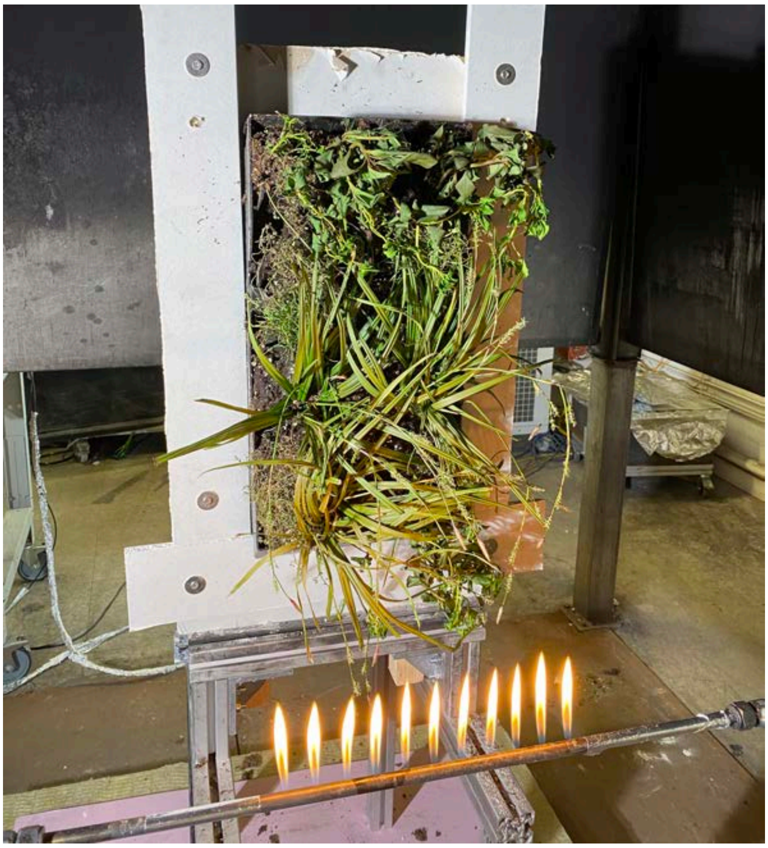

Figure 10: Pilot Flame

The burner assembly was mounted on a track, so that it could be quickly moved toward and away from the module. A track obstacle was installed so that the forward position of the pilot flame was below the canopy and close to the soil, but not close enough to ignite the plastic. See Figure 8 for a visualization.

There were two cameras positioned to record each experiment. One with a side view, and one with a portrait view. Once the data capture began, the pilot flame was rolled into its position under the module, and left there for 10 minutes. The goal of this portion of the experiment was to see how far up the canopy the flame would spread, and if that flame would also spread to the soil or module plastic. After the 10 minute exposure time ended, the pilot flame was removed to see if any remaining flame was able to sustain itself without an external heat source.

After that, testing took a more exploratory route, and a variety of actions were taken. Some of the experiments were continued by positioning the pilot flame directly under the plastic, in order to determine if flame spread was possible from that area. In other cases, the modules were salvaged and exposed to the pilot flame at a higher elevation. The objective of these experiments was to derive as much information about the response of a green wall module to fire as possible. Given the limited number of modules in our possession, some improvisation was necessary.

4. Results

The results for each of the three test series are displayed below in separate subsections.

4.1 Leaf Burning Results

The results of these tests are categorized by plant species. The goal was to form a preliminary understanding of how quickly the canopy loses moisture in the oven and how long it takes to become flammable. The results of the tests are divided by species, and organized in charts comparing the time spent in the oven and the percentage of mass lost. Their flammability category, as described in section 3.1, is indicated by colour coding. The assumption is that most of the mass lost is water, but the exact percentage cannot be established by this experiment, so these results will not discuss moisture loss directly. Instead, they will assume there is a direct correlation between mass loss and moisture loss.

4.1.1 Pachysandra Terminalis Leaf

The results of these tests were in line with the expectation that more time in the oven results in more mass loss, as shown in Figure 11. However, the mass loss seems to plateau after approximately 2 hours, even though their flammability continues to increase. The samples reached flammability after **2 hours** in the oven. These samples can be identified in the raw data in the appendix by the letter ‘P’ in the plant ID.

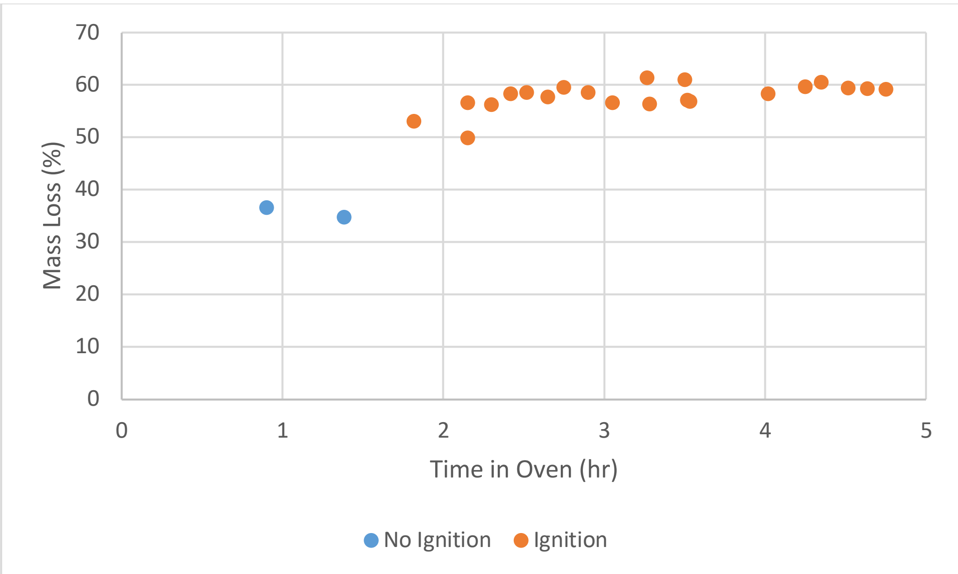

Figure 11: Pachysandra Leaf Data

4.1.2 Carex Oshimensis Leaf

Again, the results of this species of plant were relatively consistent with the expectation. The samples that spent more time in the oven lost a larger percentage of their mass, and were also more flammable, as shown in Figure 12. It appears that flammability of this species was more dependent on the amount of mass lost than the amount of time it spent in the oven. Once a leaf lost more than **60%** of its mass, it would become flammable. However, the amount of time it took to reach that point was somewhat variable. These samples can be identified in the raw data in the appendix by the letter 'C' in the plant ID.

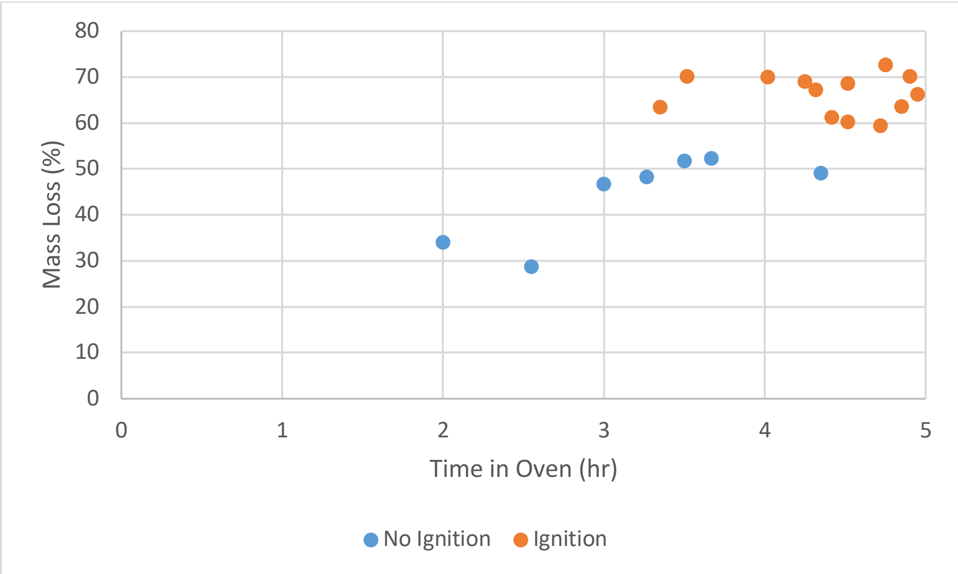

Figure 12: Carex Leaf Data

4.1.3 Thymus Vulgaris Leaf

The thymus samples did appear to lose mass at a relatively steady rate in the times that were tested, as seen in Figure 13. However, in the first hour of drying, during which time no samples were recorded, there seems to have been a period of rapid mass loss. In any case, the samples only needed **1 hour** to become flammable. The reason that two samples with ~70% mass loss failed to fully ignite is unknown. These samples can be identified in the raw data in the appendix by the letter ‘T’ in the plant ID.

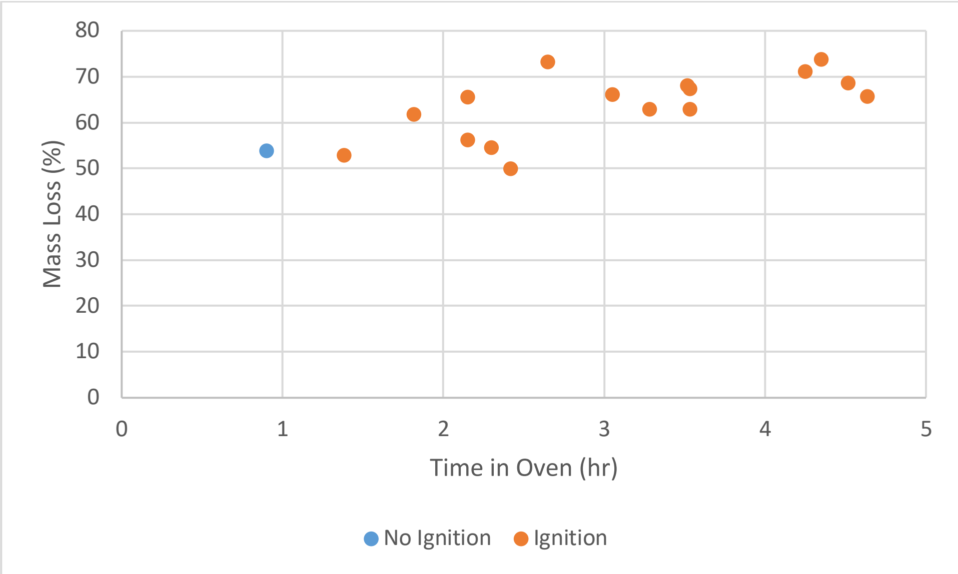

Figure 13: Thymus Leaf Data

4.1.4 Armeria Maritima Leaf

The Armeria Maritima plants that were sourced for this test were small and had very little canopy volume. Also, leaf samples were placed in the oven for 4 and 5 hours, and they all failed to ignite. Reasoning that they would not contribute a significant amount of fuel, and that their required drying time was significantly longer than the other species, the decision was made to discontinue their testing in order to focus effort elsewhere.

4.2 Plant Burning Results

The results of these tests are also categorized by plant species. The goal of this portion of the project was to determine the minimum amount of time in the oven that entire plants would need to become flammable. Due to the large amount of tests performed, they will not be discussed individually here. Instead, the peak HRR from each test is presented on the graphs in order to help draw conclusions. The FPA machine calculated HRR using two methods, Janssens and Brohez. However, only the Janssens data was used for analysis in this report. The individual HRR charts are available in the appendix.

4.2.1 Control String

In order to determine the heat release rate of the plants, it was important to be able to separate the contribution made by the heptane-soaked string. Therefore, 5 tests with a string but no plant were performed to identify the HRR of the string alone. See Figure 14 for a photo of one of the tests and Figure 15 for the results. The average from values collected is 0.935 kW.

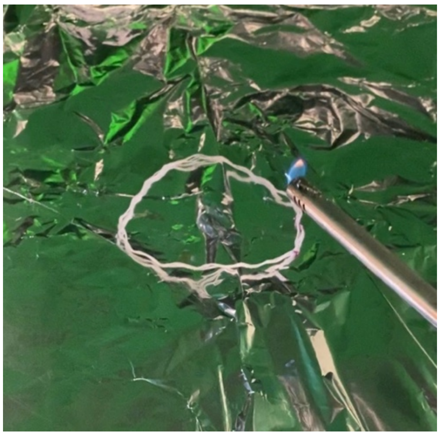

Figure 14: Burning String

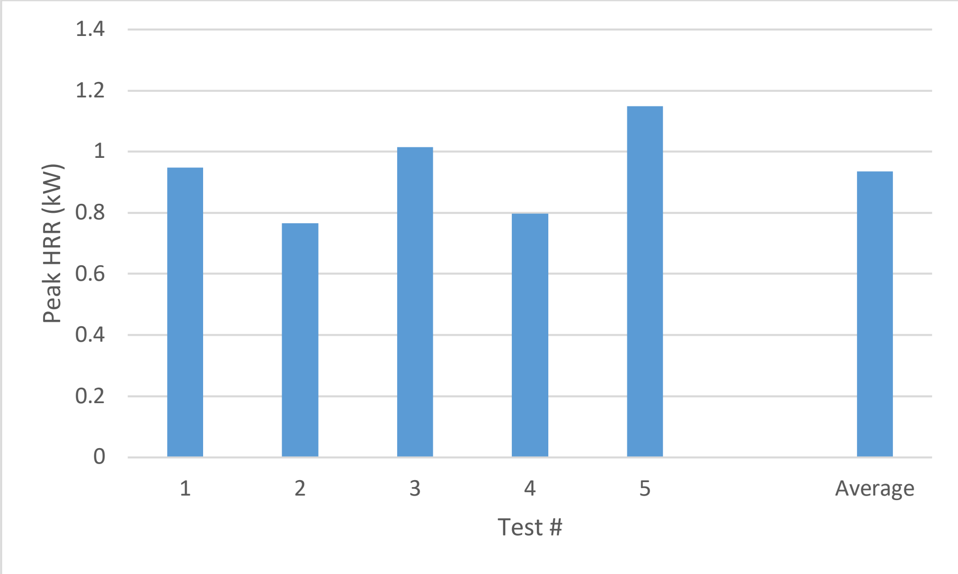

Figure 15: Control String Tests

4.2.2 Pachysandra Terminalis Plants

The raw data of these plant tests is available in the appendix, where they can be identified by the ‘G’ prefix in the test ID. See Figure 16 for a photo of the plant shortly before testing began.

Figure 16: Pachysandra Terminalis

One important objective of these tests was to establish a connection between the moisture content of the plant and the amount of time it spends in the oven. However, this proved fairly difficult to do. The calculated moisture content of the soil did not reliable decrease for the plants that spent more time in the oven. In some cases, the opposite happened, and the plants that spent more time drying actually had more moist soil, based on the trendline shown in Figure 17. This suggests that there is a flaw in the soil moisture analysis technique.

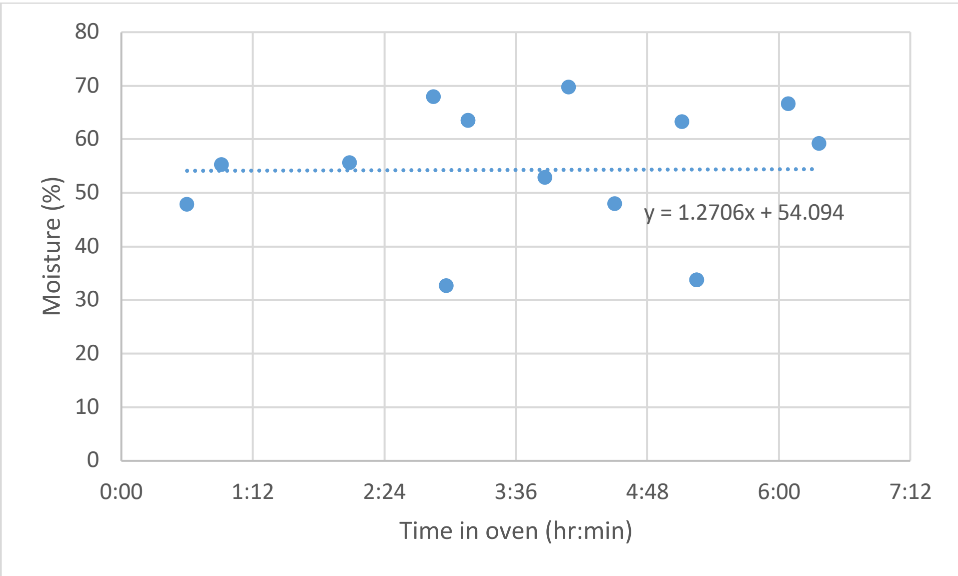

Figure 17: Pachysandra Moisture vs time in oven

However, the plants did lose mass overall the longer they spent in the oven. As one would expect, there was a clear relationship between the amount of time in the oven and the percentage of mass lost. This trend was much more predictable, as shown in Figure 18, so perhaps it is a more reliable way to measure the plant's internal chemistry and ability to ignite. However, the down side is that it would be difficult to apply this information to other plants, since the principal amount of mass includes certain things that are specific to the individual plants, such as the size of the canopy, mass of the container, and density of the soil.

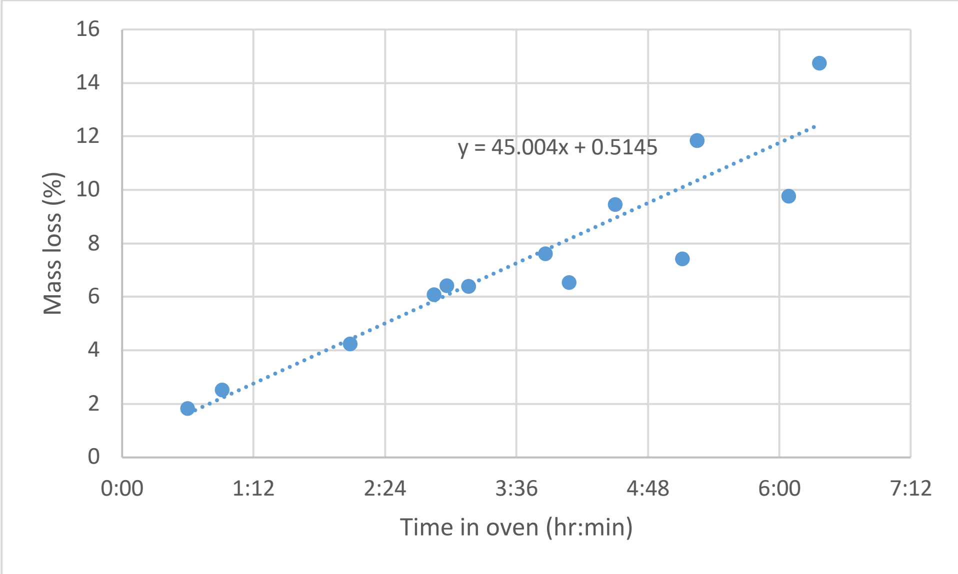

Figure 18: Pachysandra Mass loss vs time in oven

The next goal of this experiment was to establish a relationship between the moisture content of the soil and the flammability of the plant. The issue of inconsistent moisture readings poses a significant challenge to drawing any conclusions here. Using the peak heat release rate as a discrete value to characterize flammability, the expectation is that there would be a discernible relationship between that and moisture content. However, that is not necessarily the case. See Figure 19 for a visualization of the data.

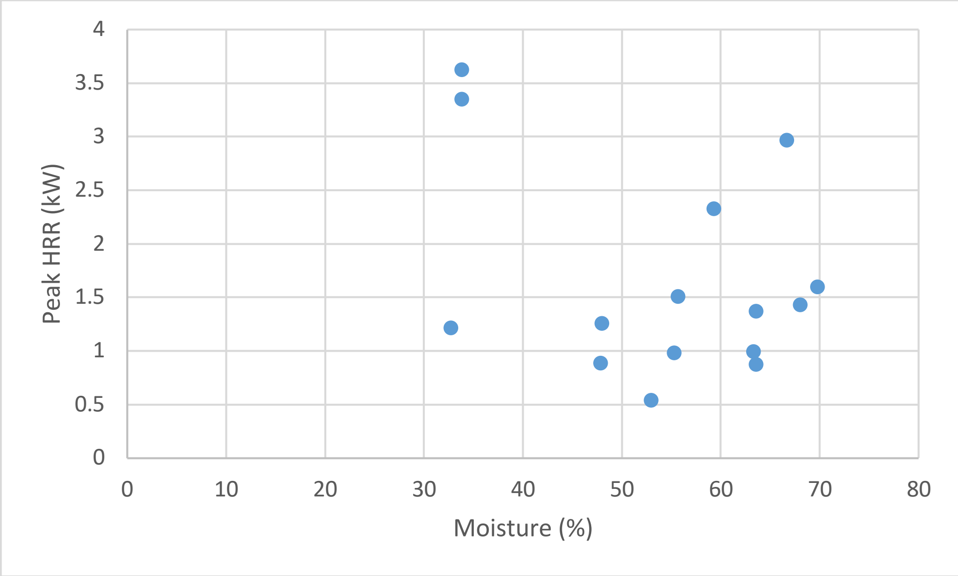

Figure 19: Pachysandra Peak HRR vs moisture content

However, when comparing the peak heat release rate to the percentage of total mass lost, there is a much more coherent relationship, which can be seen in Figure 20. Going forward, percent of mass lost will be the preferred dataset for drawing conclusions. The issue is, mass loss is heavily dependent on how much water that plant had at the time it was placed in the oven. This is a much more difficult variable to control, since the plants need to be watered periodically, and the individual plants may consume that water at different rates. Hence the initial desire to use a more objective observation like moisture content.

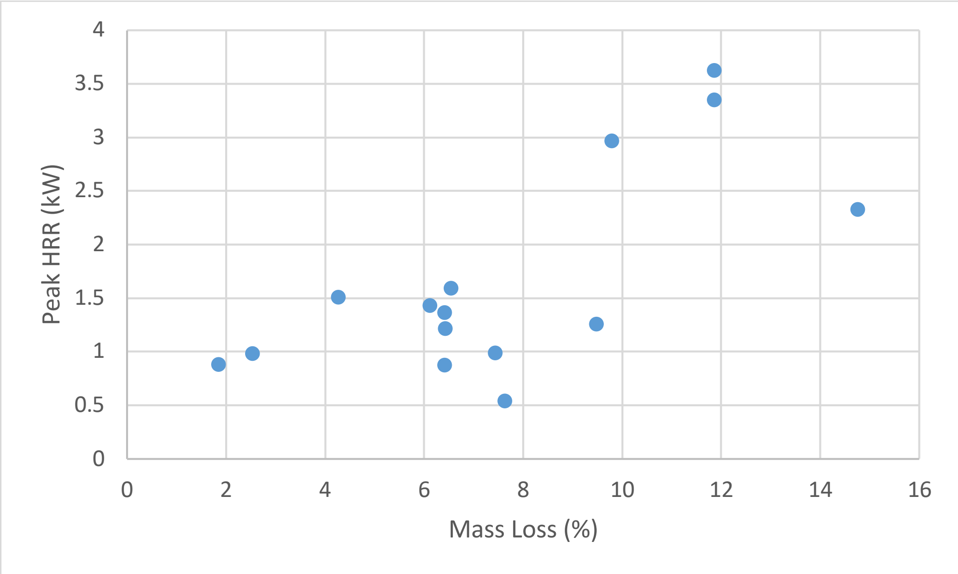

Figure 20: Pachysandra Mass loss vs Peak HRR

The final goal of this experiment was to determine the minimum amount of time in the oven needed for the plant to become flammable. This was a utilitarian objective, since the data was needed for the module testing phase of the project.

Using the data shown in Figure 21, it was determined that the Pachysandra Terminalis becomes **completely flammable** after approximately **5 hours** in the oven, and **partially flammable** after approximately **2 hours**.

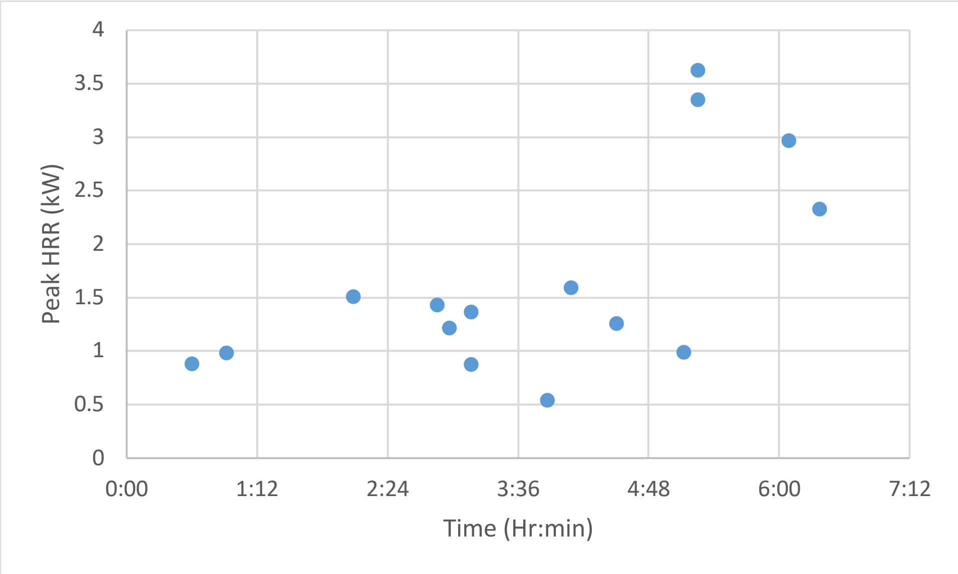

Figure 21: Pachysandra Time in oven vs peak HRR

It should also be noted that there is an extremely low HRR test (G22) that had been dried for 5 hours. However, this low reading can potentially be attributed to the fact that the canopy was twisted up, in an effort to increase the flame spread between leaves. This action raised it above the burning string by a considerable distance, which prevented a full exposure of the canopy to the flame. It only spread up the back side and was not able to spread from there to the rest of the canopy. See Figure 22 for a photo of the test.

Figure 22: G22 Test

4.2.3 Carex Oshimensis Plants

The next plant tested was the Carex Oshimensis variety. They can be identified in the raw data by the ‘B’ prefix in test ID. These plants had the largest canopy volume of the four species that were studied. They were also typically required the longest drying time in order to ignite. See Figure 23 for a photo of one of these tests.

Figure 23: Carex Oshimensis Test

The relationship between the amount of time each plant spent in the oven and the amount of mass it lost was fairly predictable for this species as well. The rate at which they lost mass is also slightly higher than the Pachysandra. See Figure 24 for a visualization of this data.

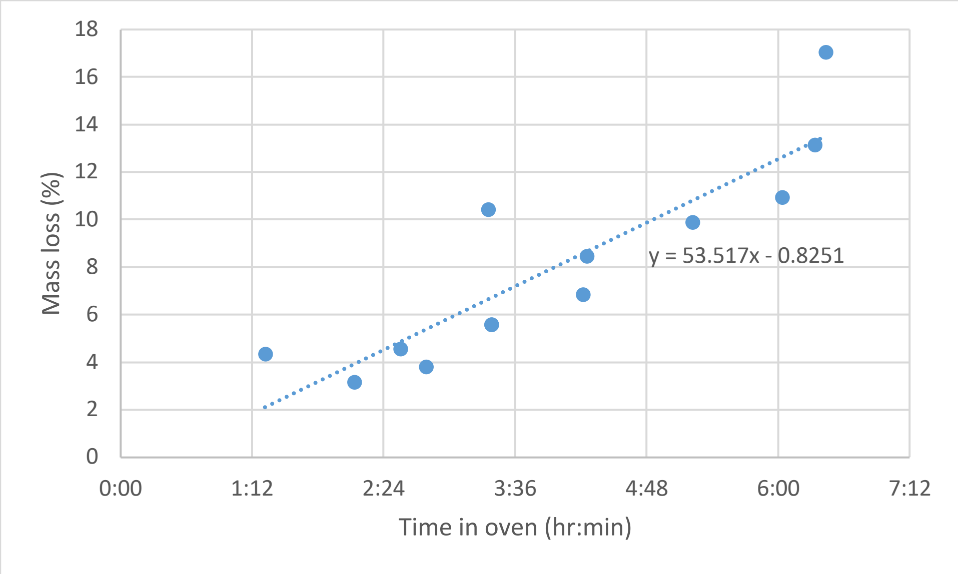

Figure 24: Carex Mass Loss vs Time in oven

The relationship between the percentage of mass lost and the peak HRR is also fairly reliable. See Figure 25 for details.

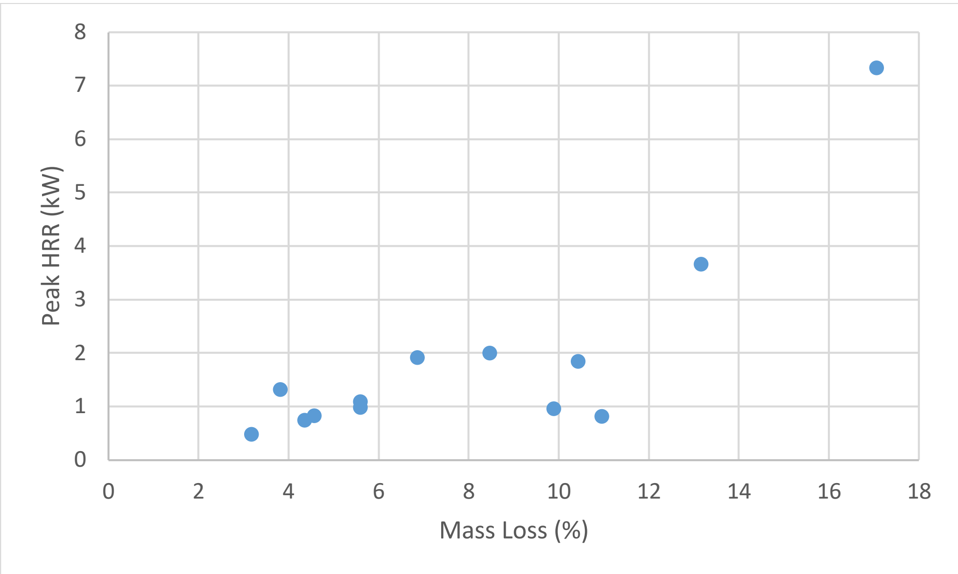

Figure 25: Carex Mass loss vs Peak HRR

Lastly, the data shown in Figure 26 was used to determine that the Carex Oshimensis becomes **completely flammable** after approximately **6 hours** in the oven, and **partially flammable** after approximately **3 hours**. This was somewhat surprising, since they had a larger mass loss rate than the Pachysandra. This may be because their canopy had more mass overall, and therefore had more canopy moisture as an overall percentage of the plant. Also, there was an additional test conducted on a plant that was left in the oven for 24 hours, in order to determine the upper limit to the heat release rate of these plants. The result was a 33.6% loss of mass and a peak heat release rate of 9.8 kW.

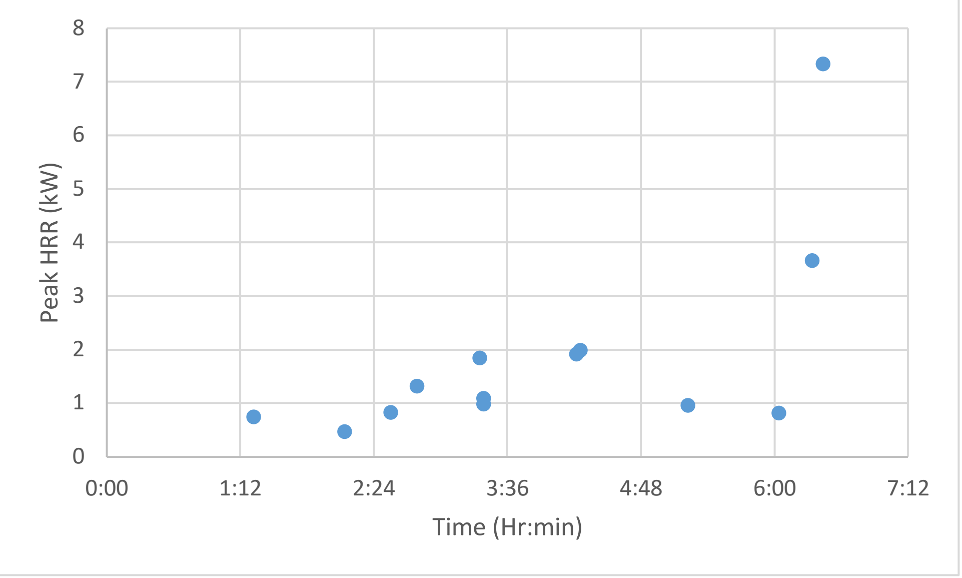

Figure 26: Carex Time in oven vs Peak HRR

4.2.4 Thymus Vulgaris Plant

The next plant tested was the Thymus Vulgaris variety. They can be identified in the raw data by the ‘T’ prefix in test ID. They had a relatively small canopy volume, but they produced a relatively large flame after only a short drying period, making them the most flammable species in the study.

The relationship between mass loss and time in the oven conforms to a predictable trendline for this species as well. Additionally, they lose moisture faster than either of the other species. However, they also had a very small plant container. See Figure 27 for details.

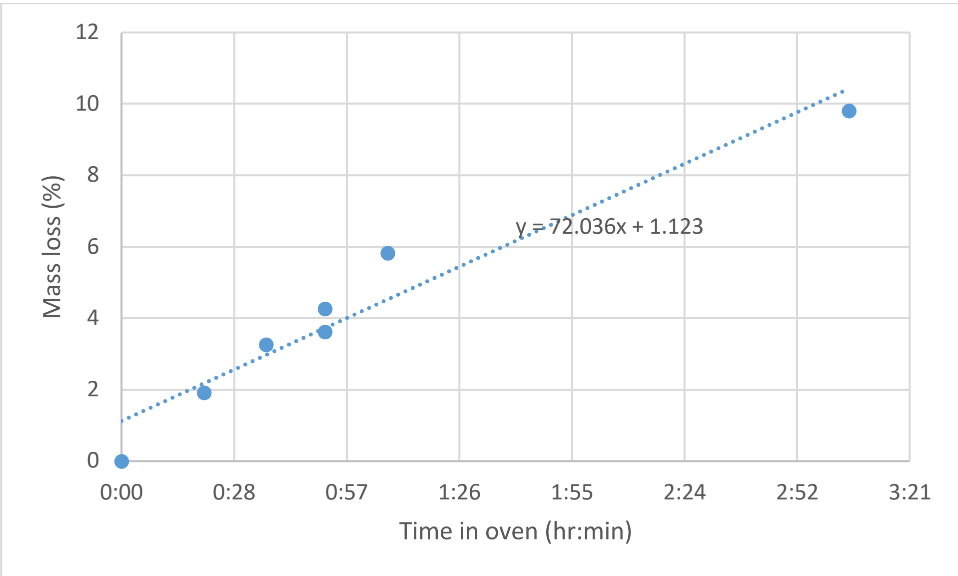

Figure 27: Thymus Mass loss vs Time in oven

The relationship between mass loss and peak HRR for the Thymus is slightly more scattered, as seen in Figure 28. However, this is may be due to the fact that fewer tests were conducted using this plant, so the dataset is not as filled out. Also, their small size could permit larger fluctuations in mass loss relatives to their overall mass.

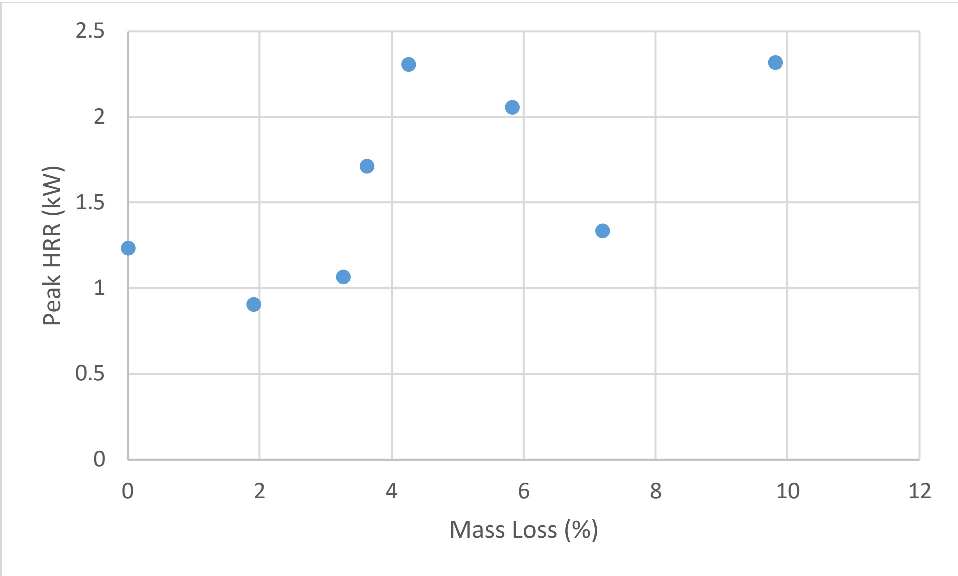

Figure 28: Thymus Mass loss vs Peak HRR

This species requires the shortest amount of drying time to become flammable. After approximately **45 minutes** in the oven, they reliably caught fire. Bear in mind that the samples used in these tests are a fraction of the size of the previous two species, so there is much less total fuel available.

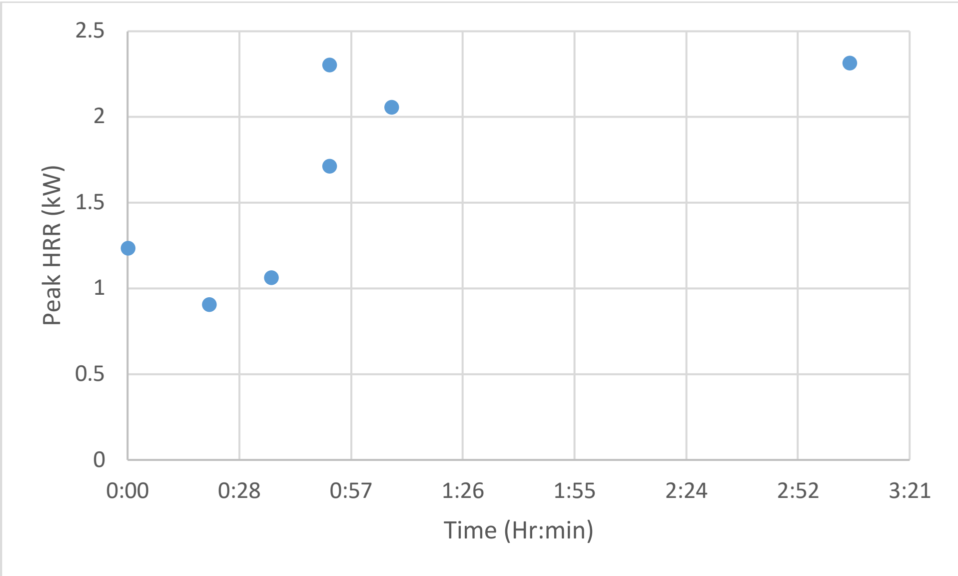

Figure 29: Thymus Time in oven vs Peak HRR

4.2.5 Armeria Maritima Plant

For the reasons described in section 4.1.4, the Armeria plants were not subjected to this test either.

4.3 Module Burning Results

This section is divided by module number. The condition of each module at the time of testing is presented, followed by a description of the test and the results. The description and results of any subsequent testing is presented as a sub-category. However, the conditions mentioned at the beginning of section may no longer be accurate, as the initial test likely changed them.

4.3.1 Module 1 Test

Table 1: Module 1 Conditions	
Time Drying	12 hours
Post-dry Weight	5.615 kg
Percent Moisture	62.56 %
Percent Mass Lost	16.77%
Test Date	March 29, 2022

Figure 30: Module 1, Post-dry

The flame spread across the plant canopy very quickly in this test. However, it fully consumed the fuel in a short period of time and then extinguished itself. Figure 31 shows pair of photos of the module after 12 seconds, where the flame is at is largest, and 45 seconds, when it has been extinguished.

	
12 seconds	45 seconds

Figure 31: Module 1 Test Photos

The heat release rate for this test peaked at ~33 kW very early on in the test and then dropped to less than 1 kW, due to a complete consumption of the canopy fuel. The mass lost by the module is also fairly steep during this first phase, but it reached a steady rate of 0.14 g/s after about 1 minute. This suggests that the soil was smouldering, either from the initial canopy fire or the continued exposure to the pilot flame. See Figure 32 and Figure 33 for the relevant trendlines. Neither the flame from the canopy or the smouldering soil were able to ignite the module plastic.

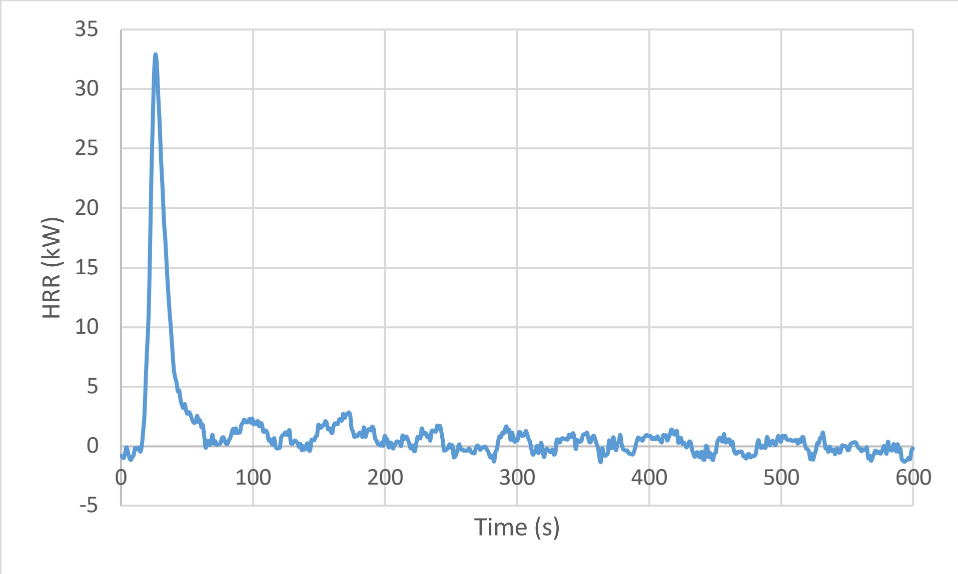

Figure 32: Module 1 HRR

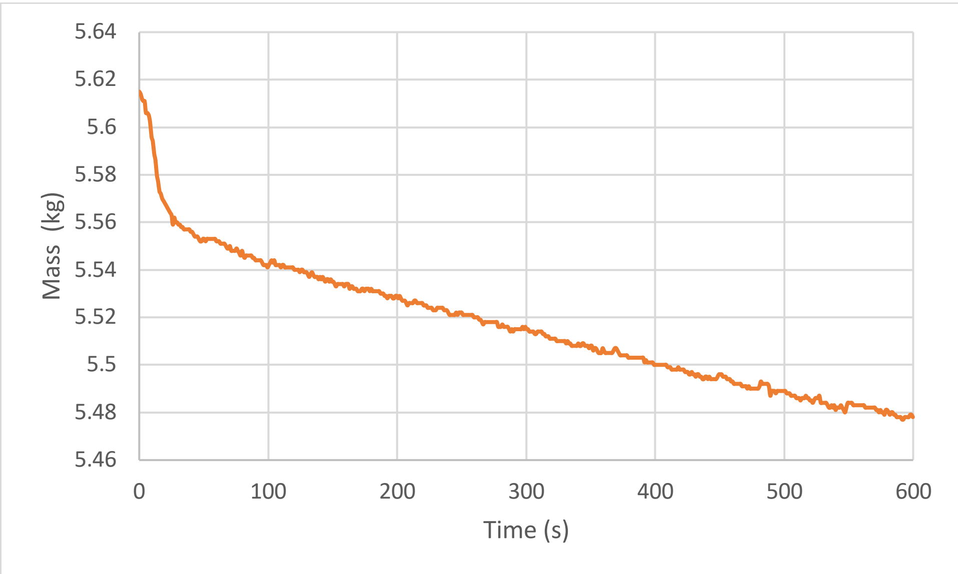

Figure 33: Module 1 Mass

4.3.1.1 Module 1 Test B

After the primary test concluded, the pilot flame was positioned under the module, so that it was in direct contact with the plastic on the bottom. After 75 second, the plastic appeared to be burning on its own, so the pilot flame was pulled away. See Figure 34 for a visualization. This flame was able to sustain itself for several minutes. The HRR from this new flame peaked at around 3.65 kW, and the mass loss increased to 0.16 g/s during this period. See Figure 35 and Figure 36 for details. However, this flame was not able to sustain itself for long. The burning plastic appeared to drip down too quickly and fell to the floor. The fire had fully extinguished itself approximately 3 minutes after the pilot flame had been retracted.

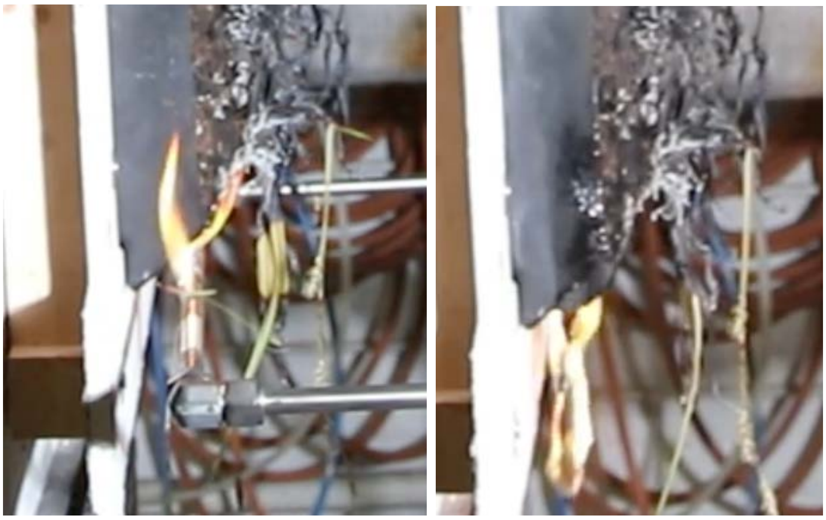

Figure 34: Lower Plastic Flame, Exposed (right), Retracted (left)

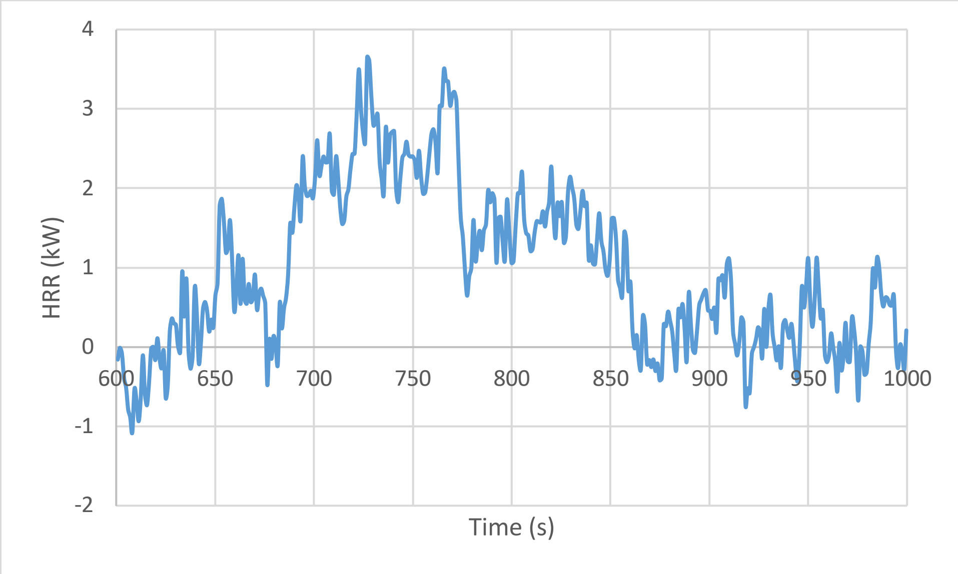

Figure 35: Module 1 Test B HRR

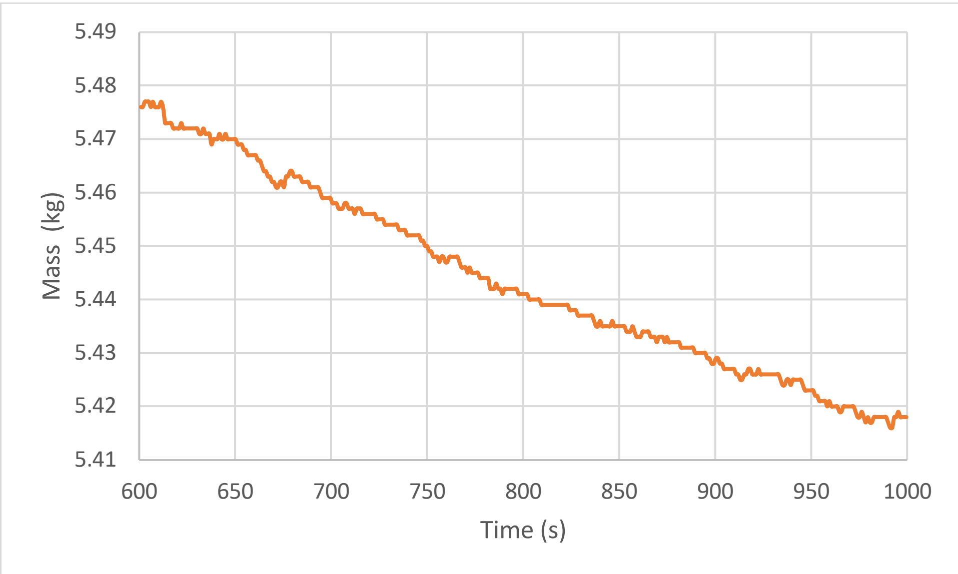

Figure 36: Module 1 Test B Mass

4.3.2 Module 2 Test

Due to the rapid burning of the canopy in the previous test, module 2 was subjected to a much shorter drying period.

Table 2: Module 2 Conditions	
Time Drying	3 hours 26 minutes
Post-dry Weight	7.159 kg
Percent Moisture	73.16 %
Percent Mass Lost	5.66 %
Test Date	March 30, 2022

Figure 37: Module 2, Post-dry

In contrast with the first test, the flame did not rapidly spread across the canopy. Instead, several of the Pachysandra terminalis and Thymus vulgaris varieties caught fire early on, but the Armeria maritima and Carex oshimensis were left relatively intact. Additionally, the aforementioned plants did not catch fire as the same time. There were four flair-ups of fire on the canopy surface in the first 90 seconds of the test, which originated at the pilot flame.

 10 seconds	 18 seconds	 29 seconds
 54 seconds	 62 seconds	 73 seconds

Figure 38: Module 2 Test Photos

The heat release rate for this test peaks at 7.2 kW at 43 seconds, which is much lower and slightly later than the peak in the module 1 test. However, it worth noting that the initial and subsequent readings were below 0. Since HRR cannot possibly be negative, this suggests that there was a calibration issue which reduced the magnitude of the overall HRR. The exact reason for this error is unknown, but a simple correction has be applied to the original data to set the HRR to 0 kW at t=0. This does not completely solve the problem, since the post canopy fire HRR is still partly negative. However, it is that largest net increase to the HRR that can be justified. The new peak HRR is 9.6 kW.

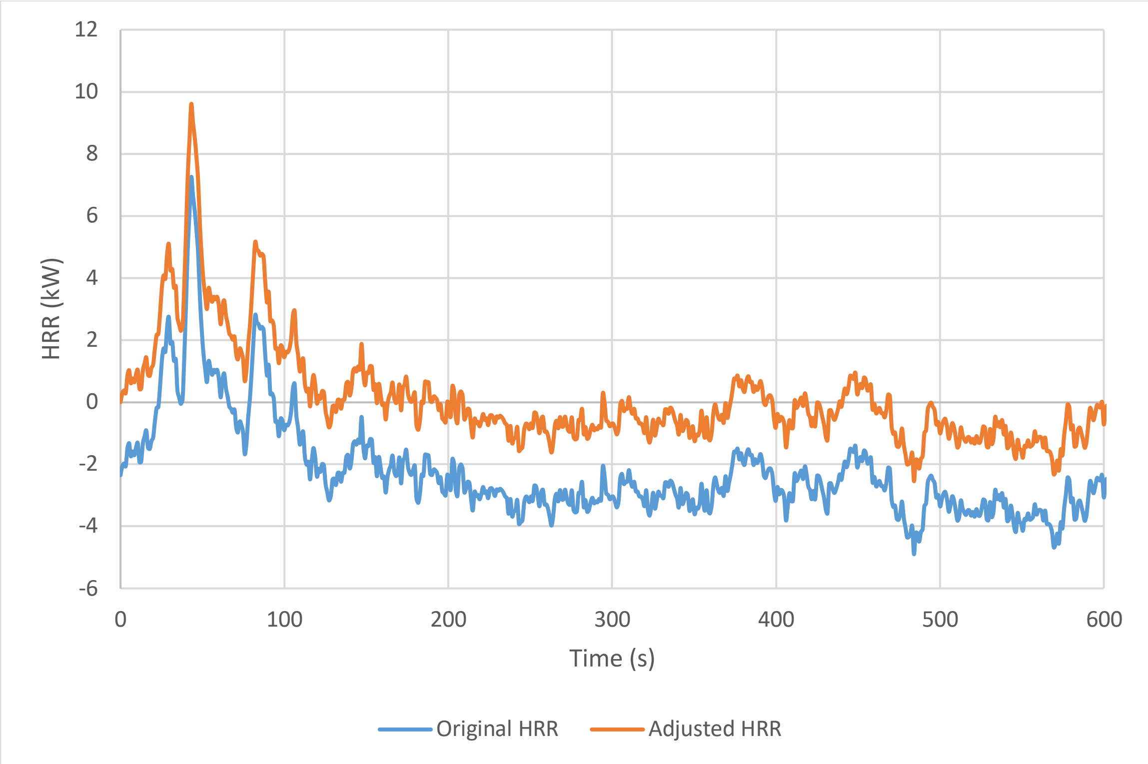

Figure 39: Module 2 HRR

The initial mass loss was very steep, similar to the module 1 test, despite a much smaller canopy fire. One potential explanation is some of the canopy material was separated from the plant by the flame and fell to the ground, removing it's mass from the scale, but did not catch fire. The mass loss rate eventually settles at 0.118 g/s, which suggests that the soil was still able to sustain a smoulder, albeit less intense than module 1. This may be due to the higher moisture content of the soil. See Figure 39 and Figure 40 for details. Again, the test was unable to cause the module plastic to catch fire.

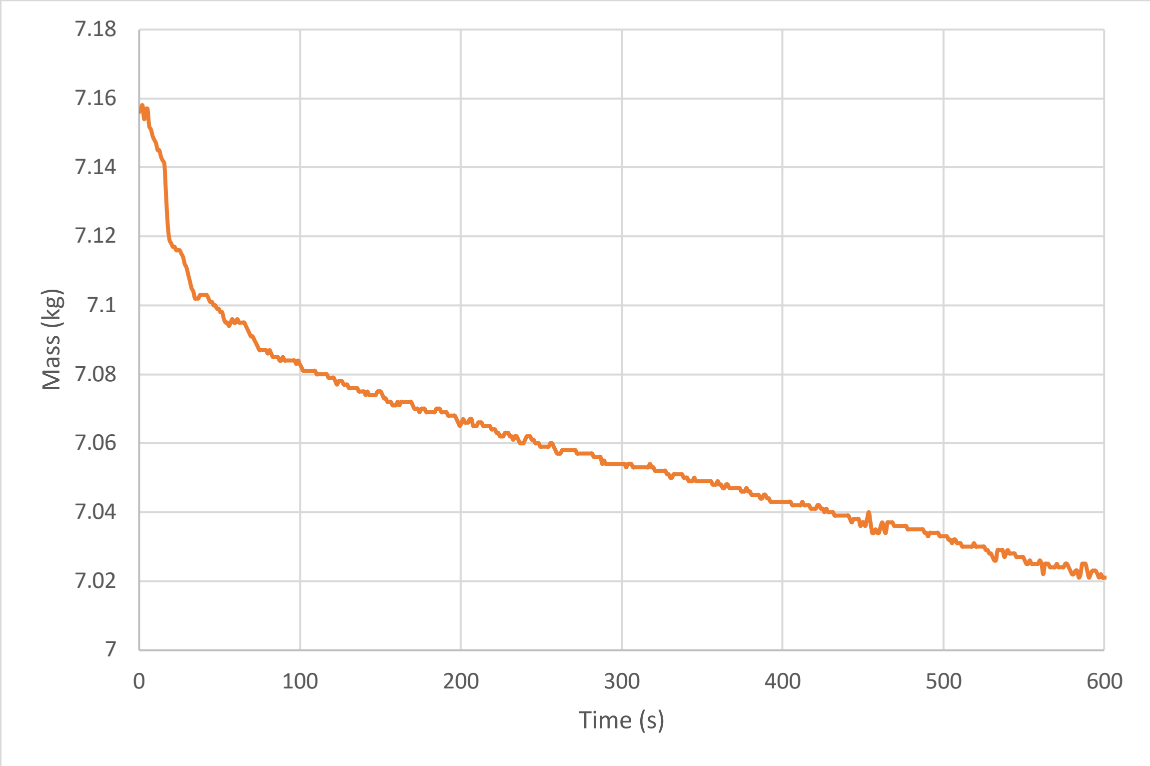

Figure 40: Module 2 Mass

The decision has been made to display the mass loss rate as a discrete value, rather than showing a chart of the mass loss rate over time. The latter may seem preferable, since it provides more detailed information. However, the amount of mass typically lost between data collection intervals was very close to the minimum resolution of the load cell, which was only 0.001kg. Therefore, the delta between recorded mass values was almost always either 0 or 1g. Refer to Figure 41 for a visualization.

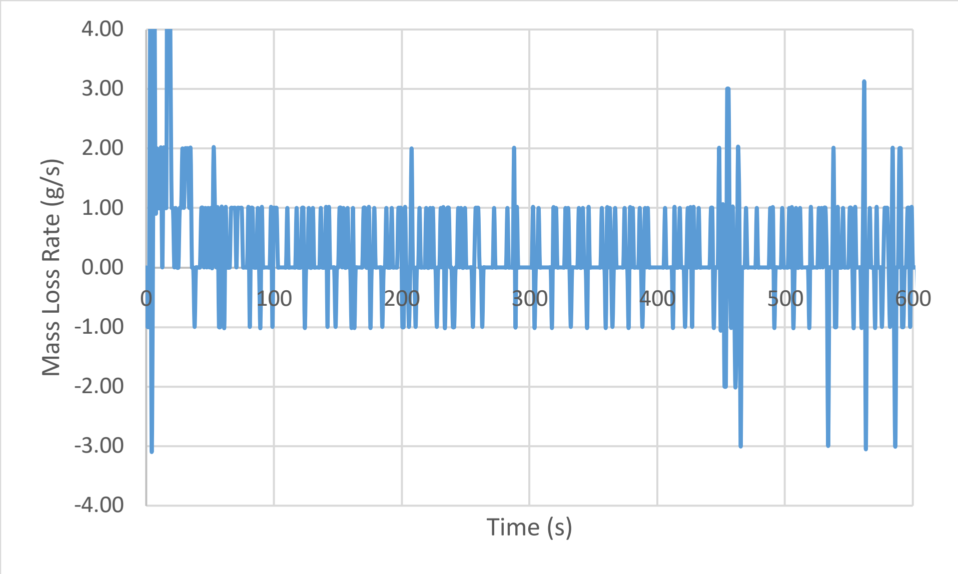

Figure 41: Module 2 Mass Loss Rate

Applying a moving average trendline was not very helpful either, since it took a very high averaging period to smooth out the trendline. This sort of defeats the point, since that reduces its accuracy at a given point in time. Refer to Figure 42 for an example trendline using a period of 25. Therefore, the mass loss rate attributed to smouldering will continue to be presented as discrete values. If there is a substantial change in this mass loss rate, multiple rates will be presented.

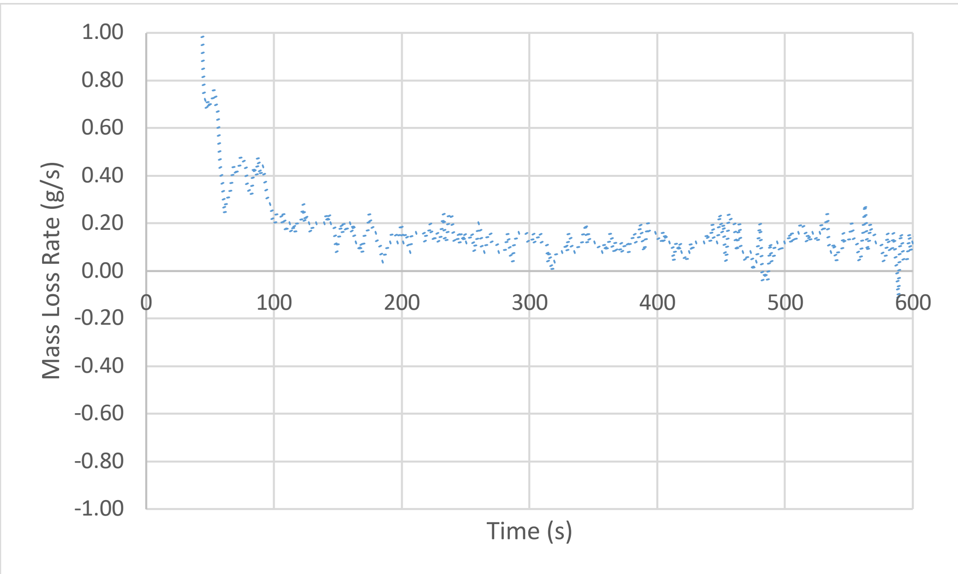

Figure 42: Module 2 Mass Loss Average (period = 25)

4.3.2.1 Module 2 Test B

After the initial test concluded, the pilot flame was retracted, and then placed directly under the lower section of the plastic approximately 11 minutes later. After 2 minutes, the module had caught fire and the pilot was retracted again. This new flame was able to sustain itself for about 2 more minutes. The calibration error persisted through this portion of the test, so the adjusted value, using the same net increase as the previous test, has been included as well. There are still a fair amount of negative values, but the trendline appears to average out to approximately 0. The original peak HRR was 3.2 kW, and the adjusted peak was 5.5 kW. The mass loss rate during this period was approximately 0.2 g/s. See Figure 43 and Figure 44 for details.

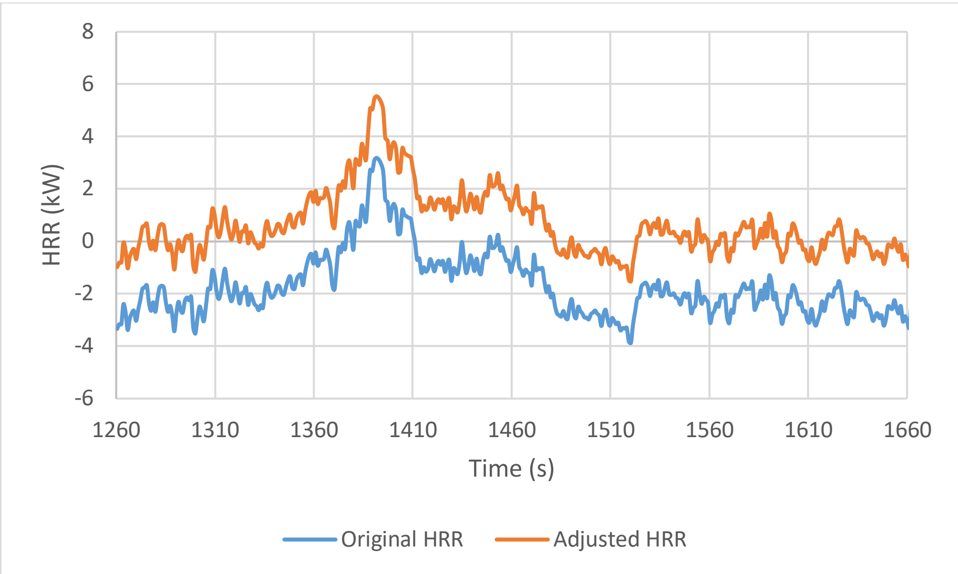

Figure 43: Module 2 Test B HRR

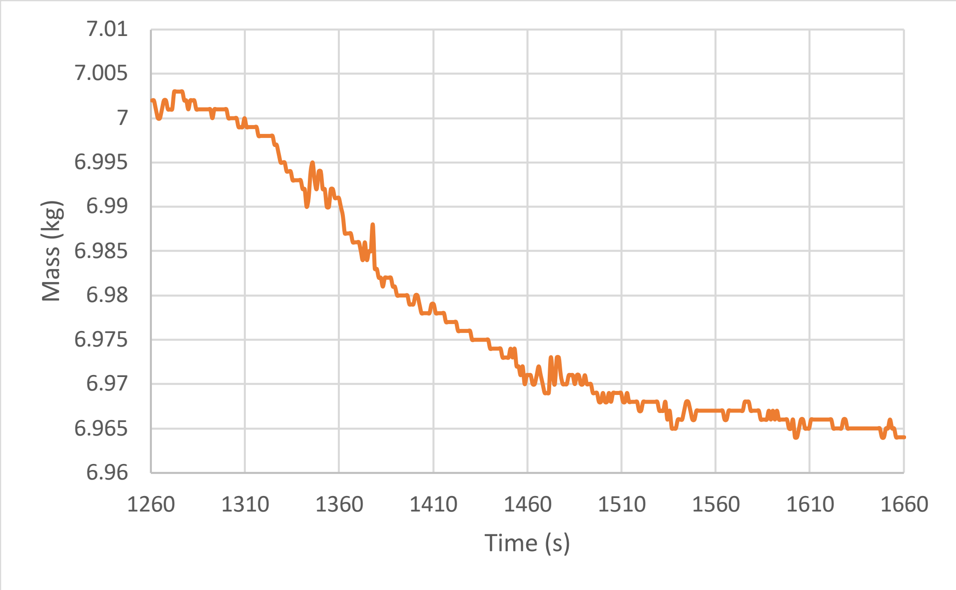

Figure 44: Module 2 Test B Mass

Following this portion of the test, the pilot flame was returned to the lower portion of the plastic and left for an extended period in order to attempt to force a spread up the module. After 2 minutes and 30 seconds, the flame was again removed. By this point, one of the soil samples had fallen out of its cell since the bottom had been mostly burned away. Again, the flame was only able to sustain itself for about 3 more minutes. One more attempt was made, with the pilot flame being placed under the module for 8 minutes. This time, a small flame was able to sustain itself on the cell wall that had its soil fall out. However, it went out after 9 minutes and was not able to expand to other parts of the module. See Figure 45 for a photo of this flame 4 minutes after the pilot had been retracted. This proves conclusively that a flame will not be able to spread up the module on its own. Also, the lack of soil in one cell did permit more burning than usual.

Figure 45: Cell flame, 4 minutes

4.3.3 Module 3 Test

This test module was intended to be used as the control test, so it was not dried out at all. Also, due to the large amount of falling material, a small tray was added below the module in an attempt to catch some of it. This was determined to be a more realistic scenario, since in a normal green wall installation, there would be a module below the burning one that could catch falling debris.

Table 3: Module 3 Conditions	
Time Drying	None
Post-dry Weight	5.81 kg
Percent Moisture	67.35 %
Percent Mass Lost	0.00 %
Test Date	March 31, 2022

Figure 46: Module 3, pre-burn

In contrast with the previous two test, which had both been dried, this module did not exhibit any flame spread on the canopy when the pilot flame was first applied. Instead, the lower two rows of plants had their stems destroyed by flame and fell to the floor, mostly missing the tray. The upper plants were wilted by exposer to the pilot flame gases, and the thyme caught fire 8 minutes into the experiment. However, this flame did not spread to any of the other plants. The test time was extended to 14 minutes in order to see if they would eventually ignite, but they did not.

Figure 47: Module 3 Test Photos

The peak HRR for this test occurred very late in the test. At 12 minutes, the HRR was 6.7 kW, although the average HRR is 3.53 kW, and it stayed at about 2 kW for the majority of the test. The previous tests both saw early HRR spikes, which dropped as soon as the canopy fire ended. The peak value within the first 10 minutes of the test was 5.4 kW. However, the peak within the first 60 seconds, which is when the other tests experienced their peak values, was only 3.65 kW. This value will discussed when comparing the peak values of the other tests.

The mass loss never experienced an initial drop like the others did, instead settling into a relatively stable loss rate of 0.309 g/s, although it does begin to level off after approximately 500 seconds. This is higher than the previous tests, which is surprising, since it was more damp, so it would be expect to smoulder less. However, because the mass loss value characterizes the smouldering rate, so it excludes the initial mass drop caused by the canopy fire. This test essentially did not have a canopy fire to exclude, so the canopy was able to spread its mass loss out over a longer period of time, as the hot gases from the pilot flame dried it out. See Figure 48 and Figure 49 for the visualization.

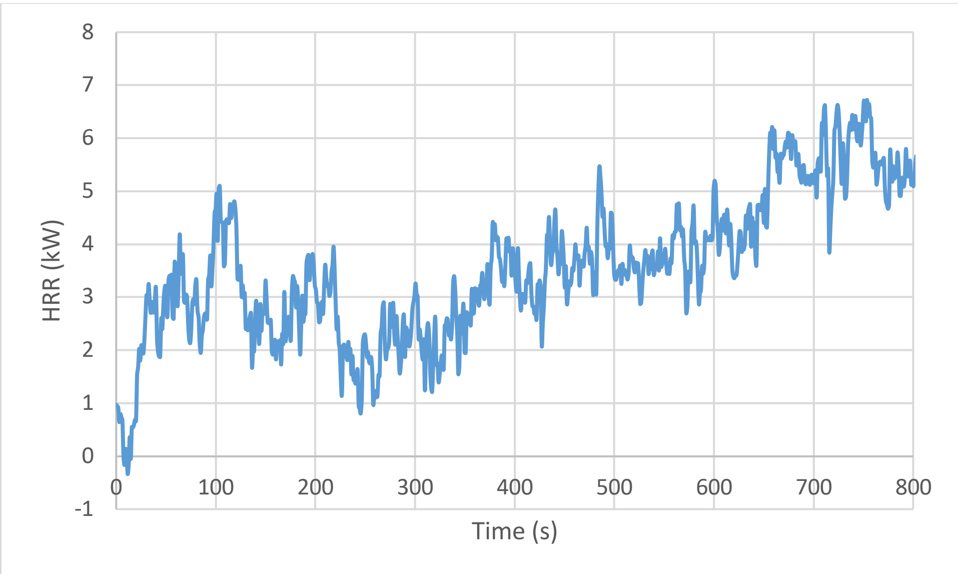

Figure 48: Module 3 HRR

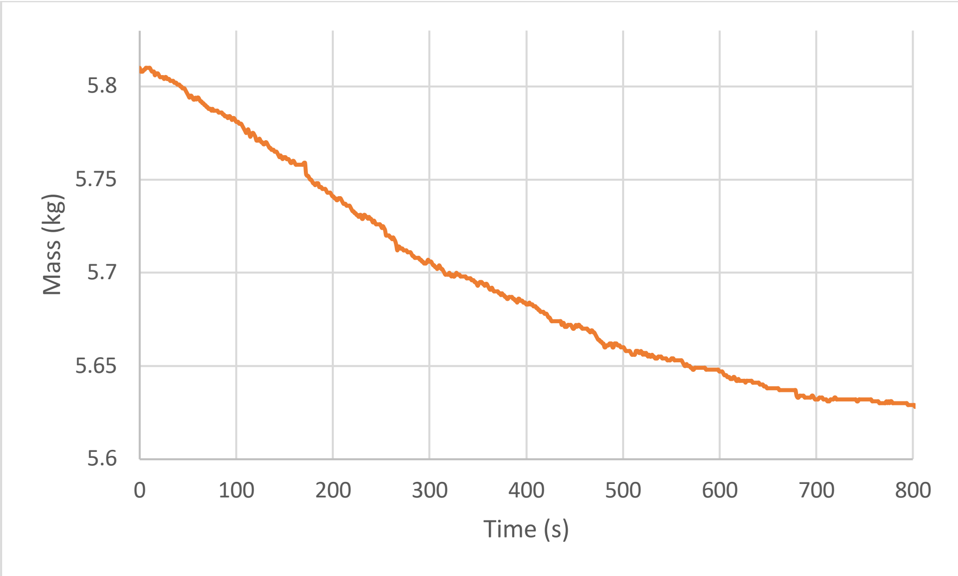

Figure 49: Module 3 Mass

4.3.3.1 Module 3 Test B

Due to the relatively good condition of the upper plants at the conclusion of the previous test, the decision was made to retest module 3 after a brief stint in the oven. This will be referred to as module 3.1. The pilot flame was moved up so that it would be the appropriate distance from the remaining canopy. However, the horizontal distance between the pilot flame and module not changed. The decision has been made to include this in the discussion of the results of the primary test, due to the useful information it provides. Only the results from the first 10 minutes will be used, and the HRR value will be omitted.

Table 4: Module 3 Test B Conditions	
Time Drying	50 minutes
Post-dry Weight	5.37 kg
Percent Moisture	65.57 %
Percent Mass Lost	1.81 % (7.71 % from pre-test mass)
Test Date	March 31, 2022

Figure 50: Module 3 Test B Post-dry

Unlike the previous test, there was some flame spread over the canopy this time. However, it was mostly limited to the Pachysandra terminalis and Thymus vulgaris varieties. The Armeria maritima and Carex oshimensis were left relatively intact, similar to the module 2 test. Again, the flame was unable to spread to the module, but some smouldering of the soil did occur.

	
5 Seconds	15 seconds

Figure 51: Module 3 Test B Photos

Since the pilot flame was positioned higher up on the module than in previous tests, it was decided to move the pilot flame to be in direct contact with the surface of the module after 14 minutes. The goal was to start burning the plastic, similar to the second part of the module 1 and 2 tests, but in a scenario where the melting plastic was able to drip down on to a lower section of the module. The pilot flame was fully retracted after 5 minutes in this position.

Figure 52: Module 3 Test B More Photos

This did allow a flame to form in one of the cells, which slowly began to spread to other cells. For the most part, this combustion took place behind the soil, and thus out of view of the camera. During the first half hour of the experiment, the average mass loss rate was 0.084 g/s. At 30 minutes, a flame had appeared on the centre partition of the bottom two cells. Shortly after that, the fire spread to the lower section of the module, and spread in a similar fashion to the other modules that had their bottom exposed to the pilot flame.

The fire melted away the bottom area, causing clumps of soil to fall off of the module. This created large mass fluctuations, which are visible in the mass trendline in Figure 54. The fire then spread to the side walls. At this point, the mass loss rate increased to an average value of approximately 0.14 g/s. However, the fire was only able to travel about half way up the module before it extinguished itself, due to the liquid plastic fuel melting away too quickly. The fire was essentially extinguished after 55 minutes, but some smouldering continued after that.

The HRR graph, shown in Figure 53, displays some problematic results. Based on the canopy fire at the beginning of the test, one would have expected a noticeable increase in HRR. However, the HRR calculated by the extraction hood shows it in the negative value, which is not possible. This issue alone does not necessarily invalidate the data. The machine calculates HRR based on the oxygen content of the air, so it does occasionally return negative values. However, the fact that it remains fairly stable while there is an active fire burning does imply that there is an error. It is also possible that the initial fire was too small to register with the analyser. In any case, the HRR begins to increase after 8 minutes, and reaches a positive value after 14 minutes. This coincides with the pilot burner being put in direct contact with the module, which would presumably increase HRR. The HRR eventually peaks nearly an hour into the test at approximately 7 kW.

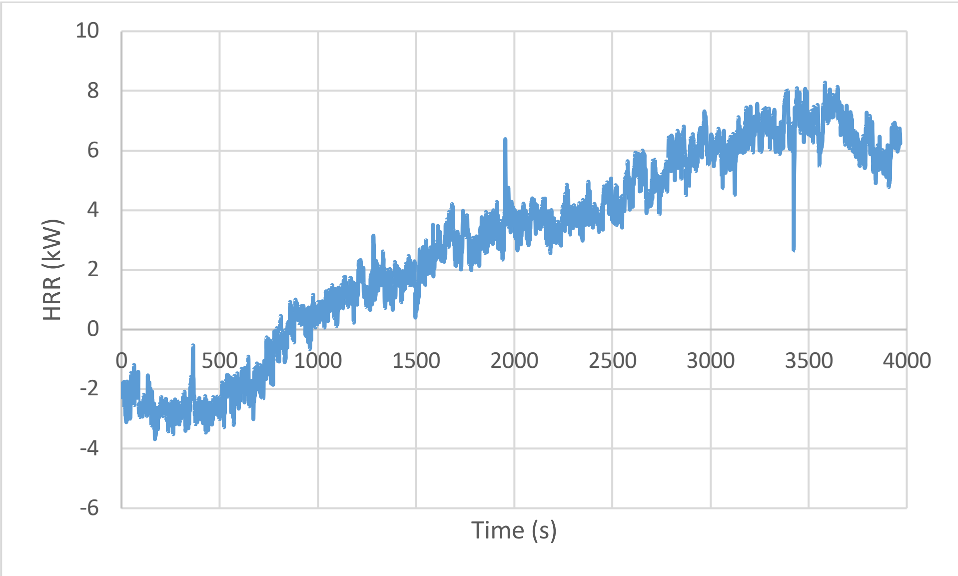

Figure 53: Module 3 Test B HRR

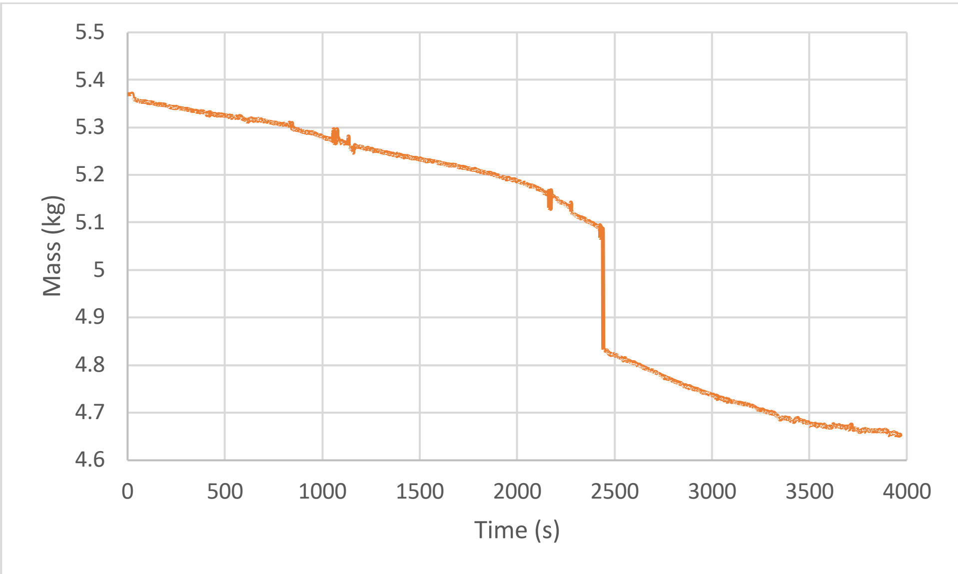

Figure 54: Module 3 Test B Mass

4.3.4 Module 4

The goal of this test was to use the information from the previous tests to make an educated guess at the minimum amount of drying time needed for the module to become flammable. The boundaries set by module tests 2 and 3B were 3.5 hours and 1 hour, respectively. Based on that information, a 2 hour drying time was selected. Unfortunately, there was an issue with the extraction hood calibration on April 1st, so the Heat Release Rate data is unusable. Efforts were made to salvage the data, but they were unsuccessful. Therefore, this section relies heavily on visual observation and mass loss data.

Table 5: Module 4 Conditions	
Time Drying	2 hours
Post-dry Weight	6.25 kg
Percent Moisture	68.39 %
Percent Mass Lost	4.21 %
Test Date	April 1, 2022

When the pilot flame was engaged, the flame quickly spread to the more flammable Thymus, and the plants located in the lower cells, but it failed to fully consume the canopy. The flame had died down after one minute, and the Armeria and Carex in the upper area were largely spared. See Figure 55 for photos of the test. There were occasional flair ups on the Pachysandra throughout the 10 minute test, caused by the hot gases from the pilot flame drying them out enough to ignite. However, this was not enough to ignite the Carex.

 18 seconds	 60 seconds
 540 seconds	 550 seconds

Figure 55: Module 4 Test Photos

As mentioned at the beginning of the section, the HRR data for this day of testing was unusable. The issue seemed to be a calibration error, where the minimum and maximum voltages for the oxygen analyser were too close together. This resulted in an O2 gradient (y = mx + b) that produced negative O2 concentration results, which is impossible. Attempts were made to salvage this information by applying an O2 gradient from a previous day. In theory, the calibration issue would not have affected the raw voltage data, so it should have been possible to reconstruct an approximate O2 concentration trendline, and then use that to calculate the HRR from oxygen consumption. This method was tested on the data from the module 1 test, using the O2 gradient from the module 3 test. The results are displayed in Figure 56, and they suggest that this is an effective way to determine HRR using alternate calibration data.

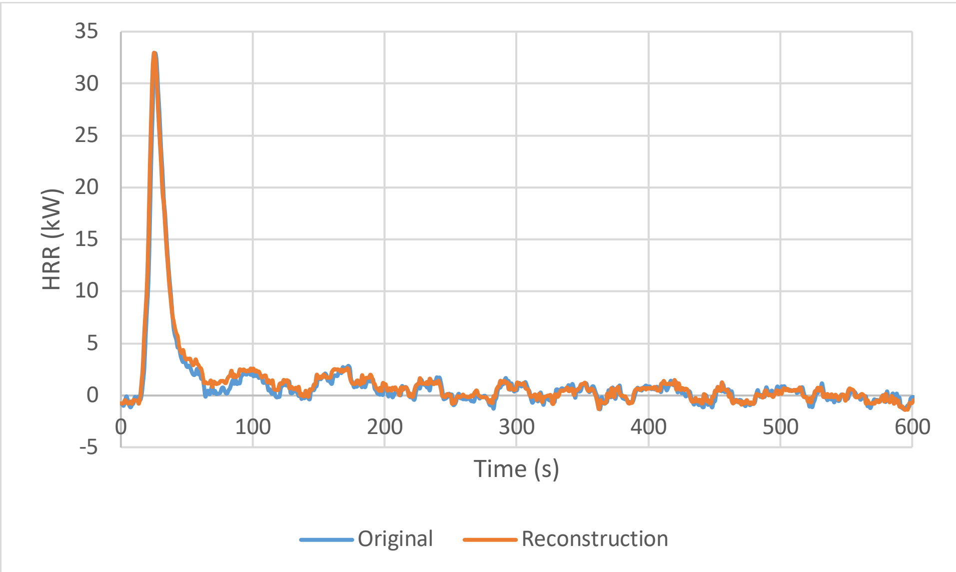

Figure 56: 'Reconstructed' HRR Example

However, when the same method was applied to the module 4 data, the method did not appear to be as effective. The ‘reconstructed’ HRR results are shown below in Figure 57, as well as the mass loss data in Figure 58. Overall, the magnitude of the HRR trendline is roughly in line with the expectation. The closest comparison would be the module 2 results (Figure

39 and Figure 40), since it also resulted in partial consumption of the canopy early in the test and a steep mass loss rate as a result. However, the module 2 HRR exhibits a steep increase that reflects the initial mass loss, due to the consumption of canopy fuel in the first minute. The ‘reconstructed’ HRR for module 4 does not show a similar increase during this period. This suggests that there was another issue with the data collection, most likely with the gas analyser. Attempts were made to reconstruct the HRR data from the other tests conducted that day, which also failed to yield acceptable results. For that reason, the results in this section will be discussed in terms of mass loss and visual observations only.

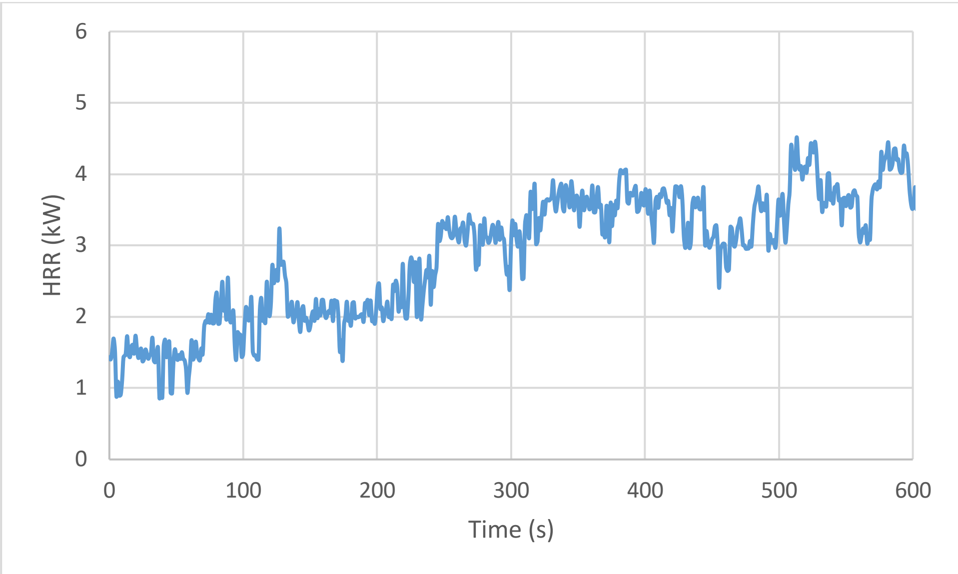

Figure 57: Module 4 HRR

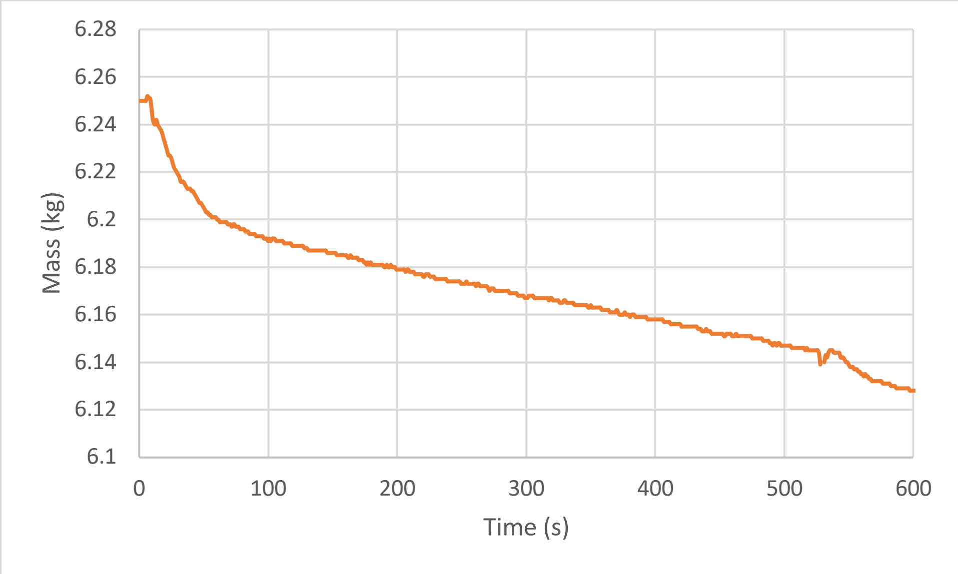

Figure 58: Module 4 Mass Loss

The initial flame extinguished itself after 1 minute, during which time the module mass decreased by approximately 0.05 kg. Module 2, the closest comparable example, lost 0.064 kg in the same amount of time, and a total of 0.073 kg by the time the fire extinguished its self after 80 seconds. This suggests that the HRR this test was slightly lower than the module 2 test. Once the canopy fire ended, there was some smouldering in the soil, as indicated by the steady mass loss through the remainder of the experiment, which averaged 0.1125 g/s. This is also slightly lower than the 0.118 g/s observed in the module 2 test. The fire was also unable to spread to the module plastic, as was the case with all previous tests.

4.3.4.1 Module 4 Test B

After the initial test concluded, the pilot flame was reoriented so that it would be at the same elevation as the 5th row from the bottom of the module. The previous 'B' tests had attempted to start a fire on the plastic from the bottom of the module, but the dripping prohibited the fire from spreading upward. If the fire started on the upper section of the module, the dripping/burning plastic could potentially spread the flame downward. The pilot flame was then pushed forward so that it was in direct contact with the soil and module. See Figure 59 for a photo of the test setup.

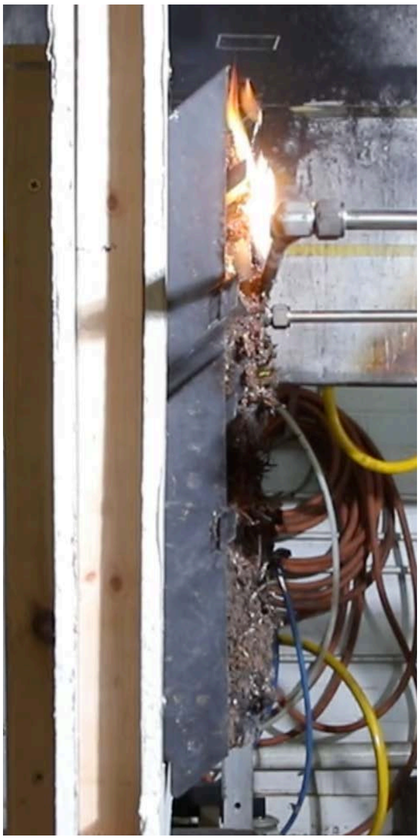

Figure 59: Module 4 Test B Setup

Unfortunately, this test required the pilot flame to make physical contact with the module in order to spread effectively. This interfered with the mass for the portion of the experiment in which it was engaged. However, it was withdrawn after 8.5 minutes, and the flame was able to sustain itself for another hour. Using the mass readings immediately before and after the pilot flame was in use, the mass loss during that time was determined to be 0.093 g/s. This is considerably lower than the mass loss experienced by the other modules, but this one did not have the canopy fire to accelerate the smouldering. Also, only one and a half cells were exposed to the pilot flame and its hot gases, due to the change in elevation, as opposed to all 6 cells when the pilot flame is at the bottom of the module. The mass loss experienced by the module after the pilot flame had been retracted can be seen in Figure 60. This test contains a number of interesting observations, and it can essentially be divided into two stages.

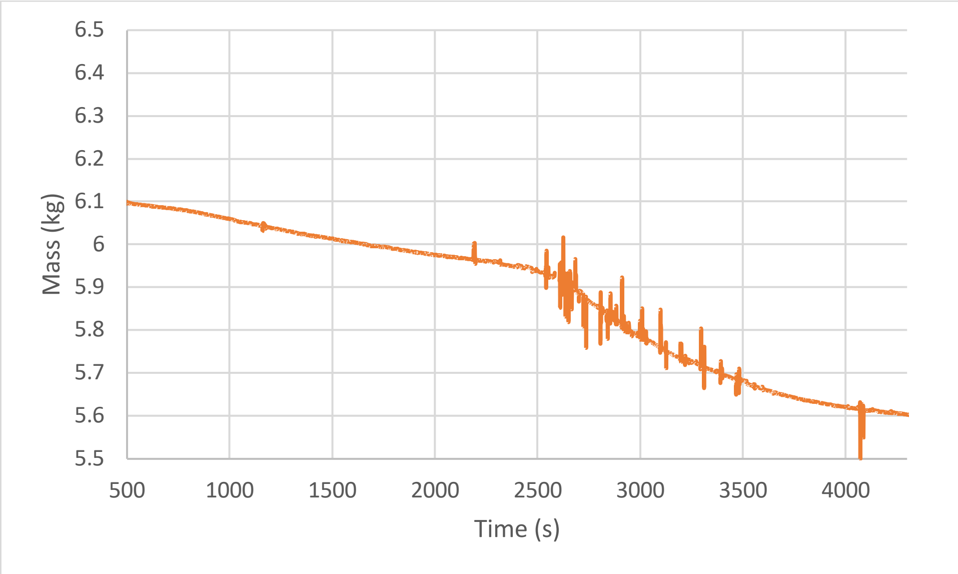

Figure 60: Module 4 Test B Mass

The first stage started when the pilot flame was retracted and ended roughly 43 minutes into the experiment. There was smouldering in the soil at this stage, which is evident from the steady mass loss rate of 0.077 g/s. This is a slight drop from the earlier value, which can be attributed to the removal of the pilot flame. Over the duration of the test, the plastic began to melt and drip down the module, which further propagated the flame. This liquid plastic was able to spread down the vertical sections of the module, and pyrolyze more plastic. See Figure 61 for photos of this phase of the experiment.

The fire was also able to spread to the cells, where the horizontal surfaces provided fuel for a fire that was both larger and longer lasting. The flame from one of these fires can be seen in the middle of the module in the 34 minute photo. At first, the soil acted as an impediment to the fire, since it physically took up most of the space in the cell. However, one of these ‘cell fires’ was eventually able to break through the back side of the module, which increased airflow to the fire and provided access to more plastic fuel. The exact time that this occurred is not known. However, 43 minutes after the test began, it was observed that part of the testing apparatus began to fail, so the break through is assumed to have happened shortly before that. This marks the second phase of the test.

9 minutes	16 minutes	34 minutes

Figure 61: Module 4 Test B photos

The issue with the apparatus was the ‘U’ shaped wooden collar, described in 3.3, that held the elevated plaster board in place. For unknown reasons, this non-structural wood began to separate from the rear plasterboard during this experiment. While this was not a threat to the overall integrity of the structure, it did create a gap that allowed airflow to the cavity between the rear wall and the module back. Refer to Figure 7 for a visualization of this cavity. In order to maintain similarity between experiments, a clamp was attached to close this gap. This added a few kilograms to the load cell, but they were edited out of the results presented in Figure 60. However, the time that the clamp was added is clearly visible, due to the large mass fluctuations and increase in the mass loss rate.

After this point, the size of the fire began to increase considerable. Based on visual observation, this produced the largest flame and smoke production that did not come from a canopy fire. With the fire burning on the inside of the cavity, it had access to all of the plastic fuel that made up the back of the module. It also began to pyrolyze the surface of the wooden support. The exact contribution of the wood to the overall mass loss is not known. See Figure 62 for photos of the fire shortly after the clamp was installed.

Figure 62: Post-breakthrough Fire

During this portion of the experiment, the mass loss rate increased significantly. The noise from the addition of the clamp makes it slightly harder to get an exact number, but an analysis of the stable sections of the data at 2789 s and 3052 s suggest a mass loss rate of 0.31 g/s, which was is the highest recorded up to that point. This mass loss rate began to slowly decrease as the cavity fire died down. After an hour of testing, the fire had shrunk considerably and the experiment was ended. The fire did not compromise the structural integrity of the module itself.

4.3.4.2 Module 2 Test C

Having observed the effects of a high elevation fire on a module with soil in it, this experiment was planned to observe the effects of a similar fire on a module without any soil. By that point, all four of the modules had been used in experiments, so module 2 was selected because the upper cells were relatively intact. The soil was then removed from the cells and it was re-installed on the testing apparatus. The test followed the same procedure as Module 4 test C. See Figure 63 for a photo of the test setup.

		
0 seconds	105s	225s
		
7 minutes	9 minutes	10 minutes

10.5 minutes	12 minutes	17 minutes

Figure 63: Module 2 Test C Photos

The result of this test was very different from the others. The module plastic quickly caught fire, and the pilot flame was retracted after only 90 seconds. The flame began melting the plastic at a much faster rate than it had in the previous test, causing the cells to collapse and fall away from the module. By 225 seconds, none of the cells remained. The average mass loss rate during this portion of the experiment was 0.24 g/s, which is fairly high, especially considering the lack of soil to smoulder and lose mass.

A steady flame was eventually able to develop on the horizontal surface at the bottom of the module, since that portion was supported by the test apparatus. Approximately 7 minutes into the test, this flame was able to break through the back wall of the module and access the cavity between the back of the module and the rear plaster board. The size of the hole gradually increased, as did the size of the flame. After 10 minutes, the exterior structure of the module began to collapse. At this time, the mass loss rate also increased to an average value of 0.84 g/s. By minute 12, it had completely fallen away from the testing apparatus. The majority of the plastic had been caught by the tray below it and continued to burn at a much lower rate for several minutes before the test was concluded and it was extinguished with water.

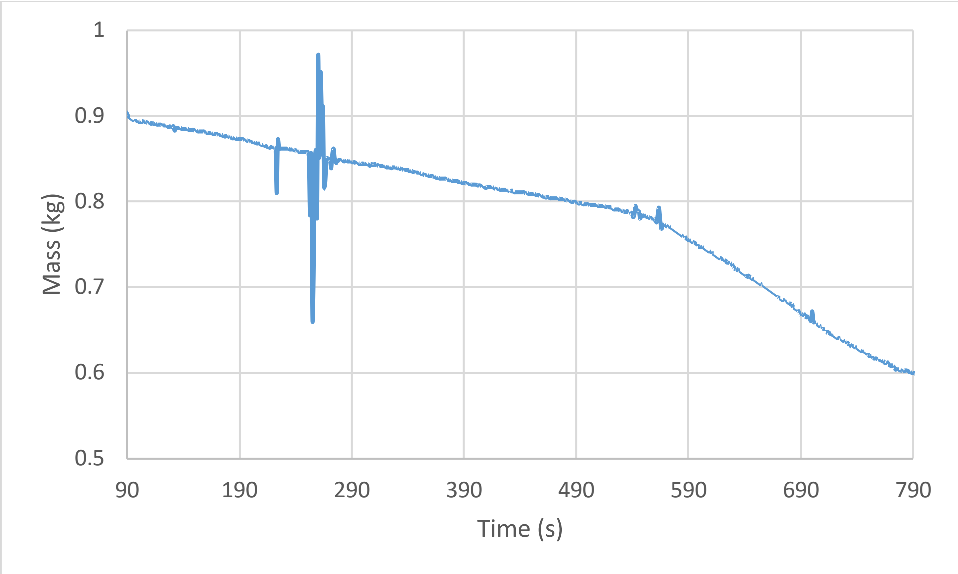

Figure 64: Module 2 Test C Mass

4.3.5 Module 1 Test C

The final test of this project was essentially intended to repeat module 4 test B, but with a much longer drying period. Module 1 was selected for this experiment, because it was in the best condition at the time. The remaining canopy material was removed and the module was placed in the oven for 24 hours. Also, by the time the drying period was initiated, it had been 2 weeks since it had last been used, during which time it was left in the lab storage area. The HRR data was correctly captured during this experiment.

Table 6: Module 1 Test C Conditions	
Time Drying	24 hours
Post-dry Weight	3.28 kg
Percent Moisture	33.6 %
Percent Mass Lost	52.6 %
Test Date	April 15, 2022

The flame quickly spread from the pilot flame to the module, causing the plastic to burn and the soil to smoulder. The pilot flame was retracted after 3 minutes, and the flame continued to spread across the module. The mass loss rate from this fire was 0.8 g/s. The only test with a higher mass loss rate was module 2 test C, which collapsed much quicker than this module. As the flame travelled down the module, the HRR steadily increased until it reached its plateau of roughly 17 kW after 6 minutes. One of the largest flames developed along the vertical wall in the centre of the module. The soil on either side of this plastic cell partition appeared to form a trench around the flame and keep it contained to that centreline and the area behind the soil. However, the flame did not appear to penetrate the back side of the module at this stage, as it had in module 4 test B. As the flame consumed the plastic cell partitions, clumps of soil began to periodically fall off. Many of these clumps did not land on the load cell, which caused drops in the mass readings. These were not edited out, and can been seen on the mass loss graph shown in Figure 67. However, they were excluded from the mass loss rate calculation. At 600 seconds, a fairly large clump fell off, which was accompanied by a noticeable drop in HRR. This suggests that soil clump may have offered some benefit to the module pyrolysis, potentially by providing structural stability to the plastic. As the cell partition plastic was gradually consumed, the fire began to die down. However, in the upper left corner, a tear began to form in the back of the module approximately 11 minutes into the test. The size of this tear increased as the fire grew in this area, and the fire began to travel down the back of the module. The fire in this cavity sustained a HRR of approximately 12 kW on its own, until it caused the fastening screw hole to fail, and the remaining module collapsed after 27 minutes. Refer to Figure 65 for photos of this experiment.

		
0 seconds	3 minutes	8.5 minutes
		
11 minutes	15 minutes	24 minutes

 27 minutes		

Figure 65: Module 1 Test C Photos

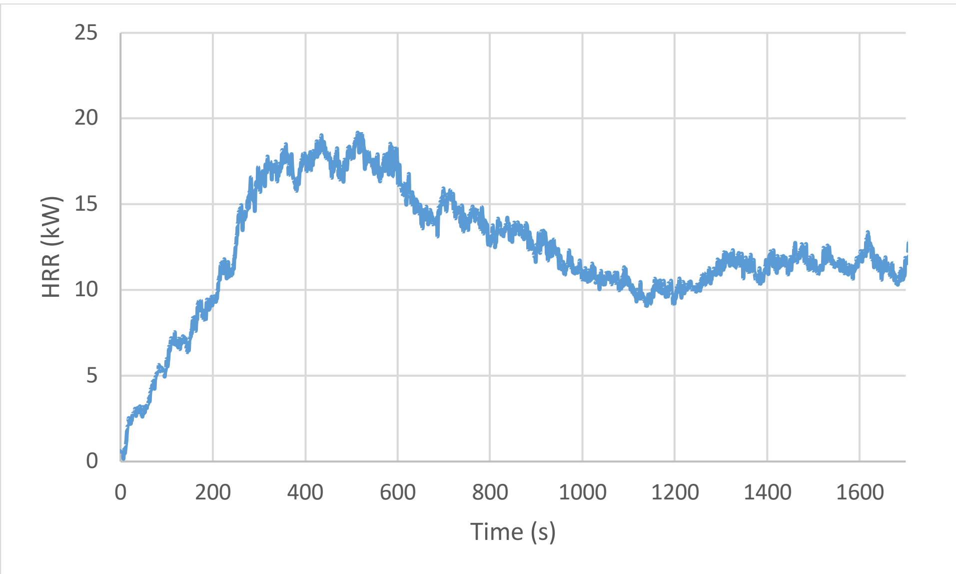

Figure 66: Module 1 Test C HRR

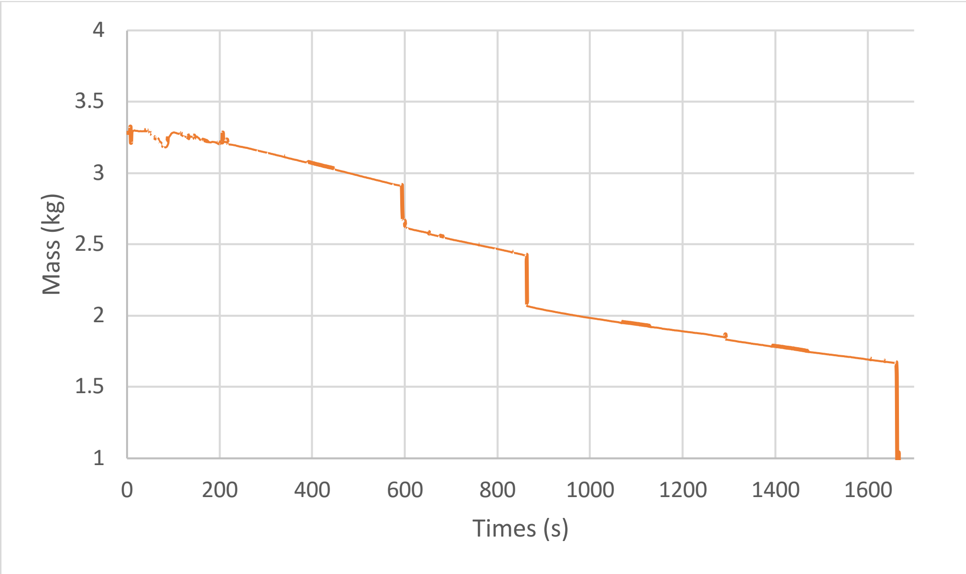

Figure 67: Module 1 Test C Mass

5. Discussion

One major flaw with the study was the method used to measure the moisture content of the soil, and its apparent lack of a connection to the amount of time that plant spent in the oven, and the heat release rate of that plant, as described in section 4.2.2. There are several possible explanations, which are discussed below. However, they all boil down to an inability to control for certain variables.

First and foremost, the technique used to collect the soil was prone to variation. Since the soil was only partially dry when the plant was removed from the oven, there was likely a gradient to the moisture content of that soil. The soil on the surface was presumably dryer than the soil at the bottom of the container. Therefore, when the sample was extracted with a spoon, the average moisture content was somewhat dependant on the amount of top soil vs bottom soil that was collected. Efforts were made to collect soil samples consistently, but some variation was likely impossible to avoid. Also, the varying amount of plant roots and other organic material captured in each soil sample likely had an impact on the final mass loss. In hindsight, it might have been better to place the entire plant in the oven for several days after the FPA test, to avoid the inherent variability of taking smaller samples. Although this would not have been practical for the module tests, since they were typically used for multiple experiments. The hope was that collecting 4 soil samples from each module would average out this variability, but that was not the case.

Another issue could stem from differences in the soil moisture prior to the drying period. The plants needed to be watered regularly, but it was not practical to plan testing around the watering schedule alone. Therefore, the soil would have been more moist on plants that had been more recently watered, and they would likely have retained some portion of that advantage through the initial drying period. The canopy, on the other hand, might not have been as affected by being more recently watered, since it was much more thermally thin than the soil and lost its moisture much faster. One possible way to account for this would have been using a lower drying temperature for the plants.

5.1 Leaf Discussion

The goal of the leaf burning experiments was to form a rough idea of how long these plants would need to stay in the oven and how much mass they would need to loss in order to become flammable. The observed minimum values for flammability are shown in Table 7. In theory, this data could also be used to estimate the mass loss rate of an entire plant canopy, independent of the mass loss rate of the soil. However, plants have vascular systems that transport water and nutrients to the canopy, which prevents them from drying out. (Britannica, 2022) Therefore, the mass loss rate of a severed leaf is not necessarily comparable to one that is still connected to the plant.

Table 7: Leaf Flammability

Species	Time in Oven (hr)	Mass Loss (%)
Pachysandra Terminalis	1.8	50
Carex Oshimensis	3.3	60
Thymus Vulgaris	1.4	50
Armeria Maritima	N/A	N/A

5.2 Plant Discussion

The goal of this section was to determine how much time in the oven it would take for the plants to become flammable, so that the module experiments could be carried out more efficiently. The observed minimum values for flammability are shown in Table 8. This mass loss was likely influenced by the soil condition prior to the drying period. These drying times were mostly longer than the individual leaves, which supports the theory that the plant vascular system helped keep them moisture in the oven. For this reason, the plants should be kept intact as much as possible during future green wall studies.

Table 8: Plant Flammability

Species	Time in Oven (hr)	Mass Loss (%)
Pachysandra Terminalis	5	9
Carex Oshimensis	6	13
Thymus Vulgaris	1	4

Armeria Maritima	N/A	N/A

5.3 Module Discussion

The results of the primary module test described in section 3.3 are displayed in Table 9. However, due to the small number of samples available, and the large amount of variability between them due to the plants, it is difficult to draw definitive conclusions from this data. With the exception of module 3, all of the tests experienced some amount of canopy burning as soon as the pilot flame was engaged. However, only module 1 had complete consumption of its canopy fuel. For the tests with shorter drying periods, only the lower and more flammable plants were burned. Additionally, the pilot flame and canopy fire did appear to reliably cause smouldering in the soil, as indicated by the mass loss rate and continued smoke production. This smouldering appears to be higher with less moist soil. However, it was difficult to separate the mass loss rate of the soil from the drying effect of the pilot flame gases. When the canopy was not dry enough to completely combust, the remaining plants were subject to lose moisture, and therefore mass, from the pilot flame hot gases. This mass loss was particularly prominent in the module 3 test, which had the least amount of canopy combustion.

The issues with the data collection in sections 4.3.2 and 4.3.4. However, there is another data collection issue that should be discussed as well. The extraction hood used is very large and is designed for fires as large as 1 MW. Many of the fires ended up being smaller than expected, and some of them may have been too small to be accurately measured with this device. In particular, the soil smouldering likely could have been more accurately measured with a smaller hood or FPA.

Table 9: Module Test Results					
#	Time in oven (hr)	Mass Lost from Drying (%)	Soil Moisture Content (%)	Peak HRR in first 60 seconds (kW)	Smouldering Mass Loss Rate (g/s)
1	12.0	16.77	62.56	33	0.140
2	3.5	5.66	73.16	7.2 (adj. 9.6)	0.118
3	0.0	0.00	67.35	3.65	0.309
3B*	0.8	7.71	65.57	N/a	0.140
4	2.0	4.21	68.39	Est. 3.65 > 7.2	0.113

*For reference only.

The issues with the method used to determine moisture content have already been discussed, however, it is worth taking a look at the module moisture results, shown in Figure 68. By increasing the overall drying time, a more coherent relationship between the two values is visible. However, the shorter drying times were primarily being studied, and this method lacks precision in that range. As with the FPA test, the mass loss % will be the preferred value for discussion of the results instead.

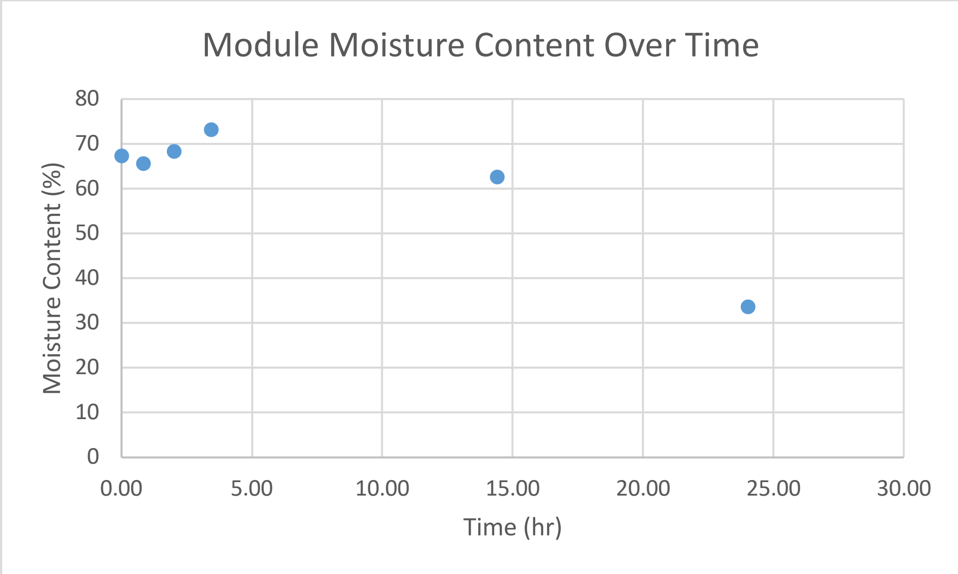

Figure 68: Module Moisture Results

Also, due to data issues, there are only three HRR data points available for empirical analysis. This is not enough information to establish definitive conclusions, but the data and a trendline have been provided in Figure 69 for use in future studies.

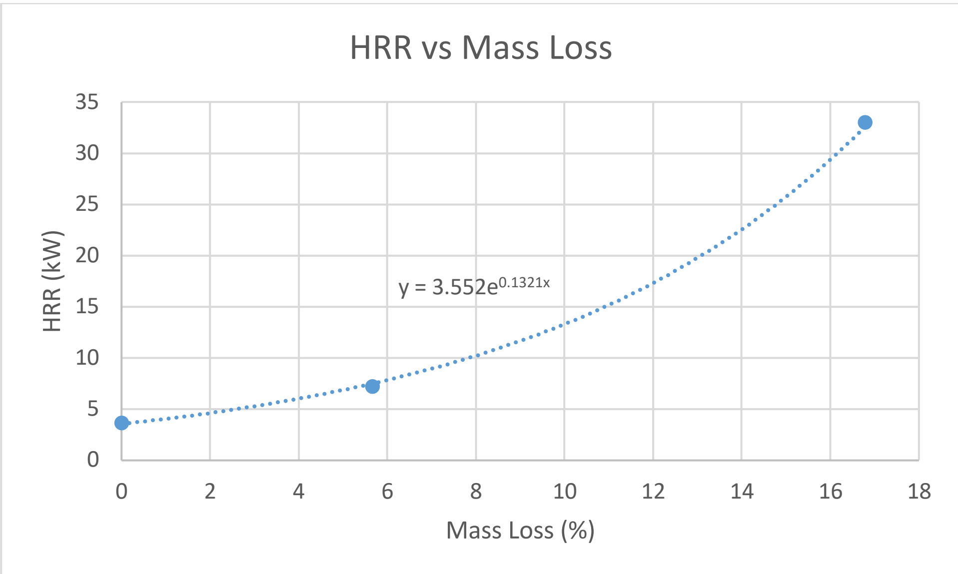

Figure 69: Module HRR vs Mass Loss Results

The most surprising outcome of the experiment series was the inability of the fire to spread from the canopy to the module plastic, at least at the scale and dryness levels tested. There were instances of smouldering being able to burn through the plastic cell partitions, but it was never able to cause outright burning on its own. The initial objective of this study was to see how dry the plants would need to be before the module burns, so this was a fairly surprising result. That is not to say that plant dryness is not a cause for concern, however. This study did show that a fire can spread up a canopy in a matter of seconds. Also, the results shown here are not necessarily scalable. A fire that is fuelled by a large number of green wall modules could certainly risk spreading to the actual plastic. That said, based on these results alone, the canopy is not the primary safety concern here.

That concludes the discussion on the empirical testing. However, the exploratory testing produced a number of interesting observations, which are discussed below. When the bottom of a module was exposed to the pilot flame, it reliably caught fire. However, these fires were unable to spread very far up the module because the plastic would melt away too quickly. It would extinguish itself after only a few minutes, regardless of the module dryness. However, there were incidents where the flame was able to last longer in a cell which had lost most of its soil during the testing, such as Module 2 Test B.

When the top section of the module was exposed to the pilot flame, the reaction is very different. The melting plastic spreads the fire to the lower section of the module, and the soil conditions do have an effect on the size of the fire. The data from the three tests is shown in Table 10, and the results are described below. If there were multiple steady mass loss rates throughout the test, the higher one is shown. Unfortunately, the HRR data from two of the tests is unavailable. Soil moisture is shown instead of percent mass lost due to drying because a large percentage of the original mass was lost due to previous experiments. Because these tests were performed on used modules, none of them had any canopy remaining. Further testing with an intact canopy is recommended.

Table 10: Upper Fire Module Test Results			
Test	Soil Moisture	Time to collapse (mins)	Mass loss rate (g/s)
2C	No soil	12	0.84
1C	33%	27	0.8
4B	68.39%	N/A	0.31

Test 2C had no soil, and produced the fastest fire spread. The cell partitions were quickly melted through and collapsed in the first few minutes, and a fire formed at the bottom of the module. This penetrated the back wall shortly after, dramatically increasing the size of the fire as began to consume the remaining plastic. This caused the module to completely collapsed after only 12 minutes. The burning rate of the post-collapse pile of plastic was considerably lower.

When the same test was carried out on a module with relatively moist soil, the fire spread was slowed down, but not prevented. The structural integrity of the module and the cells was not compromised during the hour long test. However, the fire was able to penetrate the back wall and spread into the cavity between the module and the back plaster board. Once this happened, the flame grew considerably and the mass loss rate increase from 0.077 g/s to 0.31 g/s. The cavity appeared to act as a chimney, trapping the plume between the two surfaces and restricting air entrainment until it was vented out at the top of the module, and appeared to produce particularly long flames. This observation is concerning because it suggests that a ventilated cavity fire, as described in section 2.1, could develop in this space. This could spread fire up the green wall system through the back side and ignite the upper modules more effectively than a canopy fire or exterior module fire could.

Soil, especially at the thickness used here, is an effective insulator, with thermal conductivity and diffusion values on the same order of magnitude as Brick and Concrete (Selker, 2019). The thermal barrier provided by this soil is likely the reason the module was able to retain its structural integrity. However, this is effect has its drawbacks as well. Because the module stayed in position for the duration of the test, the fire was able to burn for a longer period of time, and the soil offered no protection to the plastic back part of the module. This poses a number of potential hazards in the event of a cavity fire on a full size installation. The individual modules would stay in place longer, thereby contributing more fuel to the fire. Also, they could obstruct the view of the fire, making it more difficult for the fire brigade to locate. Lastly, because both surfaces in the cavity are fairly well insulated, the cavity will likely retain heat more effectively than it would with a more thermally thin cladding system.

This phenomenon poses a significant risk to any green wall system that does not sit flush with the wall that it is installed on, regardless of how well it has been watered. These modules are designed to be installed on top of one another, so a full sized green wall would have a much longer cavity channel, and much more plastic fuel to burn. The result of this study suggests that a fire in that cavity may be able to spread up the entirety of the installation. Additional investigation into this possibility is recommended.

This test was also carried out on a module with relatively dry soil, and the reaction was very different. The fire was able to spread rapidly over the module exterior, which was not observed with the moist soil test. This eventually caused some of the cells to collapse, and then the entire module to collapse. However, this module lasted longer than the one without soil did, despite having a higher mass loss rate throughout. This suggests that the moisture content of the soil does have an inhibiting effect on flame spread over a green wall module. However, the soil provides some structural support to a burning module, which can prolong the time to failure. The fire was also able to penetrate the back wall before it completely collapsed, although the hole was at the top of the module, so the ventilated cavity fire phenomenon could not be observed.

6. Conclusion

The influence of plant moisture on a green wall module's ability to burn was studied. The results showed that an exterior canopy fire could spread rapidly if the plants were sufficiently dry, and this could lead to smouldering in the soil. Partial canopy combustion took place at 4.2 % total mass loss, and complete combustion took place at 16.7 % total mass loss. The respective soil moisture percentages were 68.4% and 62.6%, respectively. However, these values should be treated with some scepticism, since the method used to determine moisture content was likely flawed at the drying times and temperature used in this study. Also, increased mass loss lead to increased soil smouldering. However, neither the canopy fire or soil smouldering were able to ignite the module plastic at the dryness levels tested.

In addition, the tests proved that burning plastic on the bottom of a module was unable to spread fire upward, due to the melting plastic fuel dripping away too quickly. However, if the plastic started burning on top of the module, the fire would be able to spread downward. The size of the subsequent fire, and the structural integrity of the module, were shown to be partially dependent on the soil moisture.

Lastly, the tests showed that the gap between a green wall module and building wall is a potential risk for a ventilated cavity fire, even if the module soil is relatively moist. Large scale testing of this hypothesis is recommended.

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8. Appendix

8.1 Leaf Data

Supplied in separate document

8.2 Plant Data

Supplied in separate document

8.3 FPA Data

Supplied in separate document

8.4 Module Data

Supplied in separate document