Investigating the Differences between the Self-Heating of Bark and Wood Piles during Storage Through the Use of Computer Modeling

by

Kristian Eric Johnson

A thesis submitted in conformity with the requirements for the degree of Master of Science in Forestry

Faculty of Forestry
University of Toronto

© Copyright by Kristian Johnson 2017
Investigating the Differences between the Self-Heating of Bark and Wood Piles during Storage through the Use of Computer Modeling

Kristian Eric Johnson

Master of Science in Forestry

Faculty of Forestry

University of Toronto

2017

Abstract

Due to the problems associated with self-heating in large piles of woody materials and the requirement of Nova Scotia Power to use bark to power a large biomass boiler, modeling was conducted to determine whether wood self-heating models could be used for softwood bark piles. During an approximately 100 day storage trial of 2 large bark dominated biomass piles, the piles peaked at average temperatures of 40° C and 50° C. Modeling in Comsol Multiphysics with bark parameters obtained from physical characterization tests of material from trial site yielded accurate predictions of pile temperature, with pile 2 being simulated closely by the model. Pile heating differed between sections of the piles, with the bottoms of the pile heating much slower than the rest. A sensitivity analysis yielded several parameters, which affected the model, such as bulk density, thermal conductivity, pile height and microbial death and growth rates.
Acknowledgments

I would like to thank my supervisor, Dr. Sally Krigstin for her support and guidance, my committee members Dr. Suzanne Wetzel, Dr. Tat Smith, and Dr. Dominik Roser, Jacques Lirette and Sylvain Volpe of FPInnovations for their support in the trial, my colleagues at the University of Toronto, particularly, Dr. Javed Sameni, Dr. PeiYu Kuo, Gireesh Gupta and Nicolas Tanguy for their help and advice. Lastly, I would like to thank my brother, Ryan Johnson, my parents, David Johnson and Elizabeth Walker, and my partner, Haley Dickson for all of their love, support and patience.
Table of Contents

Abstract.............................................................................................................................................. ii
Acknowledgments............................................................................................................................... iii
Table of Figures ....................................................................................................................................... vi
Table of Tables ....................................................................................................................................... vi
1. Background ....................................................................................................................................... 1
   1.1 Wood-chip Storage in Canadian Context .................................................................................... 1
   1.2 Inherent Differences Between Bark and Wood ......................................................................... 1
   1.3 Pile Self-Heating Drivers ........................................................................................................... 5
   1.4 Effects of Storage on Chip Quality and Temperature ............................................................... 7
   1.5 Wood Pile Models .................................................................................................................... 9
   1.6 The Model ............................................................................................................................... 11
2. Statement of Problem ....................................................................................................................... 14
3. Purpose of Study ............................................................................................................................... 15
4. Hypotheses ....................................................................................................................................... 15
5. Significance ....................................................................................................................................... 16
6. Methodology ..................................................................................................................................... 16
   6.1 Materials ..................................................................................................................................... 16
   6.2. Experiment Site ...................................................................................................................... 17
      6.2.1 Port Hawkesbury Paper ...................................................................................................... 17
      6.2.2 Trial Site ............................................................................................................................ 18
   6.3 Large-scale Trials .................................................................................................................... 18
   6.4 Bark Characterization Methodology ........................................................................................ 20
      6.4.1 Parameter Methodology Preamble .................................................................................... 20
      6.4.2 Moisture Content ............................................................................................................. 20
      6.4.3 Ash Content ..................................................................................................................... 20
      6.4.4 Green Weight Bulk Density ............................................................................................. 21
      6.4.5 Elemental Analysis .......................................................................................................... 21
      6.4.6 Higher heating value (HHV) methodology ...................................................................... 21
      6.4.7 Thermogravimetric Analyzer ......................................................................................... 22
      6.4.8 Free Sugar Methodology ................................................................................................. 22
   6.5 Model Methodology ................................................................................................................ 23
6.5.1 Geometry ......................................................................................................................... 23
6.5.2 Physics ............................................................................................................................ 24
6.5.3 Mesh and Solution ............................................................................................................. 25

7. Results ................................................................................................................................... 25

7.1 Field Trial ............................................................................................................................. 25
  7.1.1 Handling the data ............................................................................................................ 25
  7.1.2 Temperature variation among pile sections .................................................................... 27

7.2 Bark Parameters ................................................................................................................... 29

7.3 Model Results ...................................................................................................................... 35

8. Discussion .............................................................................................................................. 36

8.1 Considerations ...................................................................................................................... 36

8.2 Bark Parameters .................................................................................................................. 38
  8.2.1 Basic Characteristics ..................................................................................................... 38
  8.2.2 Parameters That Differed From Wood ......................................................................... 39
  8.2.3 Parameters That Did Not Differ .................................................................................... 40
  8.2.4 Modeled Thermal Parameters ....................................................................................... 41

8.3 Trial Discussion .................................................................................................................... 42
  8.3.1 Trial Setup and Results ................................................................................................ 42
  8.3.2 Comparison of Model Results with Trial Results ......................................................... 44

8.4 Sensitivity Analysis .............................................................................................................. 45
  8.4.1 Biological Heating Source ............................................................................................ 47
  8.4.2 Physical Parameters ...................................................................................................... 49
  8.4.3 Parameters Which Caused No Effect ............................................................................ 51

9. Recommendations .................................................................................................................. 53

10. Conclusions ........................................................................................................................ 55

11. References ........................................................................................................................... 56
List of Figures

Figure 1: Left: diagram from Fengel & Wegener (1989) showing a microscopic view of the tree cell system, with P indicating the heterogeneous phloem, C indicating the cambium and X indicating the more homogenous xylem. Right: a diagram from Kramer (1979) showing a macroscopic view of the bark, with the phloem and rhytidome indicated .......................................................... 2
Figure 2: Photo taken on-site of the material waiting to be piled ................................................. 17
Figure 3: Left: front of pile, Right: side of pile. Above, temperature probe placement in the control pile. Below, temperature probe placement in the piped pile. Locations appear as diamonds, and pipe appears as dashed line .................................................. 19
Figure 4: Comsol model geometry, trapezoid on top is the bark pile-geometry while the rectangle at the bottom is a soil geometry .......................................................... 23
Figure 5: Pile 1 temperature when all sections are weighted equally ........................................ 26
Figure 6: Pile 2 temperature when all sections are weighted equally ........................................ 27
Figure 7: Change in standard deviation of pile temperature for Middle section of Pile 2 .......... 27
Figure 8: Average temperature of all probes for each Pile 1 section over time ......................... 28
Figure 9: Average temperature of all probes for each Pile 2 section over time ......................... 29
Figure 10: Average bark pile temperature compared to simulations with wood values and bark values 36
Figure 11: Sensitivity analysis of kinetic factors ..................................................................... 37
Figure 12: Average pile temperatures compared to ambient temperature over the course of the trial .. 43
Figure 13: Average temperature profile of piles 1 and 2 .......................................................... 44
Figure 14: Sensitivity analysis of easily degradable fraction ..................................................... 47
Figure 15: Sensitivity analysis of microbial death rate ............................................................... 49
Figure 16: Sensitivity analysis for thermal conductivity parameter ......................................... 50
Figure 17: Sensitivity analysis of bulk density .................................................................... 51
Figure 18: Sensitivity analysis of pile height ....................................................................... 52
Figure 19: Sensitivity analysis of change in initial oxygen concentration ............................... 52
Figure 20: Sensitivity analysis of specific growth rate ............................................................. 53

List of Tables

Table 1: Ash content of various Eastern Canadian softwoods from Isenberg et al. (1980) .............. 4
Table 2: Total quantity of bark extractives extracted using alcohol-benzene from Isenberg et al. (1980) ........................................................................................................... 5
Table 3: Nomenclature for self-heating model equations .......................................................... 12
Table 4: Probe count and temperatures of each pile section for both piles ............................... 26
Table 5: Summary of the values used for simulation the wood pile and the bark pile, with justifications as to why each parameters chosen. Parameters in green were changed to bark values .................................................. 30
Table 6: Oven dry weight of Eastern Canadian softwood bark and wood as reported by Miles & Smith (2009) ........................................................................................................... 39
Table 7: Higher heating values for bark and stem wood from 6 Eastern Canadian softwoods from Singh (1986) ........................................................................................................... 41
Table 8: Summary of results of sensitivity analysis for tested parameters ............................... 46
1. Background

1.1 Wood-chip Storage in Canadian Context

In Canada, bioenergy accounts for 0.52 EJ of the energy budget, which in 2012 totalled 8.73 EJ in secondary energy consumption, with wood waste being the primary source of fuel (NRCan, 2015). Of this bioenergy consumption, approximately half of all industrial bioenergy use was from the pulp and paper industry (NEB, 2014). Biomass used for industrial pulp and paper energy production typically comes from residues generated by the manufacturing of wood-products, as 40% of the feedstock are waste by-products that can be used for bioenergy (Hakkila & Parikka, 2002). Biomass-fed power plants require great transport distances for their feedstock, with optimal stand distance being up to 500 km from the plant, and optimal forwarding distance being within 500 m of the boiler (Thiffault, 2015). A review by Thiffault et al. (2015) outlined the storage of woodchips as an important step for managing the wood bioenergy supply chain, with storage of materials allowing greater flexibility for responding to energy demands and thus increasing efficiency. Storing biomass in piles provides a buffer for managing these energy demands, particularly in the northern latitudes where severe winter conditions can impede the supply of biomass (Nurmi, 1999).

The storage of wood in small particle sizes such as sawdust and chips, however, poses major risks, with wood-chip piles spontaneously combusting from the heat their internal processes produce (Ferrero et al., 2009), and the fungi proliferating in the piles causing respiratory problems in individuals working with these piles (Sebastian et al., 2006). In addition to the effects on health, it is generally accepted that storage of biomass results in the loss of approximately 1% of its dry mass per month (Garstang et al., 2002), however, this can range as high as 27% over a 15-month period (Afazal et al., 2010) to as low as 0.07% per month (Gjølsjø, 1988). It is, therefore, necessary to study the ways in which the storage of forest biomass can be optimized in order to minimize the risk of self-ignition, matter loss and increase the safety of these piles.

1.2 Inherent Differences Between Bark and Wood

In addition to white wood, bark and whole tree residues are also utilized as feedstocks for bioenergy. These different types of feedstocks have an impact on the fuel quality and temperature change of a comminuted forest residue pile (Thörnqvist, 1988). While bark is a plentiful by-product of the pulp and timber industries and is often used as a source for bioenergy generation (Kaltschmitt et al., 2013), with typically 10-20% of the stem and 25-30% of material in the branches and crown being composed of bark (Fengel & Wegener, 1989), research focusing on the storage of bark-dominated
storage piles is uncommon. In order to understand how bark differs from other tree components, its physiological structure and how this affects its properties must be examined.

The growth and cellular composition of bark will be discussed first. Bark grows on the outer layer of the cambium as a heterogeneous section called the phloem, whereas wood grows on the other side of the cambium as a more homogenous section called the xylem (Thomas, 2000). The inner phloem of gymnosperms is composed of vertically oriented sieve cells, parenchyma (which often contain resins, crystals and tannins), and fibres, as well as, transversely oriented parenchyma and often albuminous cells. The role of the phloem is to transport sugars and sap throughout the tree via the sieve cells, whereas the xylem of gymnosperms is mainly composed vertically of tracheids, with a small fraction of parenchyma and epithelial cells, as well as, transversely oriented ray tracheids, ray parenchyma and epithelial cells, the xylem primarily move water up through the tree, but they also facilitate the movement of some sugars and sap (Thomas, 2000; Kramer & Kozlowski, 1979). The outer portion of the bark, called the rhytidome, is a section of dead material in the form of obliterated phloem, which are expanded parenchyma and collapsed sieve cells, and are interspersed with layers of periderm which are sections of the bark that are air and water tight (Thomas, 2000; Fengel & Wegener, 1989). Figure 1 visualizes this with diagrams displaying the microscopic and macroscopic views of the inner and outer bark.

Figure 1: Left: diagram from Fengel & Wegener (1989) showing a microscopic view of the tree cell system, with P indicating the heterogeneous phloem, C indicating the cambium and X indicating the more homogenous xylem. Right: a diagram from Kramer (1979) showing a macroscopic view of the bark, with the phloem and rhytidome indicated
One of the most important roles for the bark is to control the loss of water and to defend the tree from microbial attack; because of this bark contains a different chemical composition, with higher abundance of polyphenols, suberin and other extractives, as well as a smaller fraction of polysaccharides (Fengel & Wegener, 1989). Compared to xylem, a larger portion of the phloem is composed of parenchyma (described in Krigstín & Wetzel, 2016). Parenchyma are responsible for respiration in trees, which survive after the material is chipped and is a key source of heat generation in forest residue piles (Hajny et al., 1967). Thus the respiration of bark can have a more pronounced role in wood-chip pile heating. This distinct physiological structure results in bark having some unique physical properties when compared to wood, with it being described as mechanically weaker and possessing lower heat transfer coefficients (Martin, 1969; Cassens, 1974 described by Fengel & Wegener, 1989). This can be seen in practical scenarios with panels produced from Norway spruce (*Picea abies*) bark having a 30% lower thermal conductivity than those produced from wood at the same density (Kain et al., 2012). This lower thermal conductivity means that bark can retain more heat.

In addition to these physiological differences, there are chemical differences between wood and bark; bark typically contains higher concentrations of lignin, extractives and ash than wood (USDA, 1971). Softwood barks typically have a lignin content of 40-55% compared to wood, which contains only 25-30%. Black spruce follows this trend with its bark containing 45.84% lignin and wood containing 27.25% (USDA, 1971; Isenberg et al., 1980). Table 1 displays ash content data collected for several Canadian boreal species from a review by Isenberg et al. (1980). Overall, the bark had an average ash content of 2.16% while the wood had an ash content of 0.27%, showing that, on average, the bark has nearly 10 times the ash content.

The sugars in bark mainly come in the form of glucose, but are also present in other forms such as mannose, galactose and xylose, in small quantities (Fengel & Wegener, 1989). Furthermore, some species of softwoods can have unusually high amounts of other sugars, with a review from the USDA (1971) noting that species such as eastern white pine (*Pinus strobus*) had up to 15% xylose and eastern hemlock had up to 13% mannose (USDA, 1971). Barks typically contain smaller fractions of sugars compared to sapwood (Fengel & Wegener, 1989; Song et al., 2012; Kemppainen et al., 2014). A study from Robinson et al. (2002) using increasing fractions of bark mixed into wood found a 65% decrease in total sugar content when the bark content was raised from 0 to 100% for Douglas-fir (*Pseudotsuga menziesii*) which was freshly harvested and frozen. These sugars provide fuel for respiration and are a valuable food source for fungi.
Table 1: Ash content of various Eastern Canadian softwoods from Isenberg et al. (1980)

<table>
<thead>
<tr>
<th>Species</th>
<th>Bark ash content (%)</th>
<th>Wood ash content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Spruce (Picea mariana)</td>
<td>2.2</td>
<td>0.3</td>
</tr>
<tr>
<td>White Spruce (Picea glauca)</td>
<td>3.8</td>
<td>0.26</td>
</tr>
<tr>
<td>Eastern White Pine (Pinus strobus)</td>
<td>1.2</td>
<td>0.25</td>
</tr>
<tr>
<td>Jack Pine (Pinus banksiana)</td>
<td>1.7</td>
<td>0.24</td>
</tr>
<tr>
<td>Red Pine (Pinus resinosa)</td>
<td>1.3</td>
<td>0.23</td>
</tr>
<tr>
<td>Balsam Fir (Abies balsamea)</td>
<td>2.8</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>2.16</strong></td>
<td><strong>0.27</strong></td>
</tr>
</tbody>
</table>

Another of these chemical differences is a much higher abundance of extractives in barks (Fengel & Wegener, 1989). Table 2 outlines the total fraction of extractives from the bark and wood of several Canadian boreal species, with the average bark extractive content being 14.5% and the average wood extractive content being 3.6%. Royer et al. (2013) describes some of the extractives coming from Canadian boreal species such as Jack Pine (Pinus banksiana) and Black Spruce (Picea mariana), which contain a number of anti-microbial and fungicidal agents. Some of these extractives include polyphenolic compounds such as pinosylvin and pinocembrin, and terpenoids such as torulosol. (Royer et al., 2013; Hanawa et al., 2001; Bower & Rowe, 1967). There is contradictory evidence, however, to the impact of these extractives during the degradation of bark with some studies suggesting some piles containing bark were found to have more fungal spores and degradation, and that these extractives may be rapidly decomposed when they enter the soil system (Thörnqvist 1985; USDA, 1971). As described by Preston et al. (2009), bark contains more nutrients than wood, with higher quantities of nitrogen, phosphorous, potassium, calcium, and Magnesium. In wood, the low nitrogen rates can limit the growth of fungi, as they require it for producing enzymes to degrade woody material (Thörnqvist, 1985). It could, therefore, be possible that the higher nitrogen contents of bark could reduce the limitations present for fungi on wood.
### Table 2: Total quantity of bark extractives extracted using alcohol-benzene from Isenberg et al. (1980)

<table>
<thead>
<tr>
<th>Species</th>
<th>Bark Extractives (%)</th>
<th>Wood Extractives (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Spruce</td>
<td>14.7</td>
<td>2.2</td>
</tr>
<tr>
<td>White Spruce</td>
<td>16.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Eastern White Pine</td>
<td>15.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Jack Pine</td>
<td>15.3</td>
<td>4.0</td>
</tr>
<tr>
<td>Red Pine</td>
<td>5.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Balsam Fir</td>
<td>19.5</td>
<td>3.2</td>
</tr>
<tr>
<td>Average</td>
<td>14.5</td>
<td>3.6</td>
</tr>
</tbody>
</table>

In summary, bark and wood are very different substrates; bark is a heterogeneous section of the tree with different cell types and a different role than wood. This different role derives from its unique physical and chemical properties, which can affect bark’s use as a fuel, such as its high ash content. It also affects its degradation, with fungi having lower quantities of sugars to consume, which could impact its rate of self-heating. Bark is also less thermally conductive than wood, which can reduce its ability to dissipate heat when stored. Given these factors it is, therefore, important to examine how wood and bark will self-heat differently, as well as whether wood based self-heating models are adaptable to bark piles.

### 1.3 Pile Self-Heating Drivers

One of the biggest risks associated with the storage of wood-chips is self-heating, which occurs as a result of the various chemical and biological processes occurring over time in the pile and which can drive the pile to spontaneously combust. These mechanisms include the respiration of fungi and surviving tree parenchyma (Fengel & Wegener, 1989; Kubler, 1990), thermo-oxidative reaction between oxygen and exposed lignocellulosic material (Kubler, 1987) and the condensation of water vapour into the material (Armstrong, 1973).

The first of these processes is heat generated by microbial activity. This occurs when fungi grow in a wood-chip pile. As microbes break down the wood and consume the sugars in the pile, they respire, which produces energy (Fengel & Wegener, 1989; Kubler, 1990). Wood-chip microbes, however, have limitations and their effects can be minimal under certain conditions. Fungi require moisture content in
the substrate to be higher than the fibre saturation point, or about 24-28% (dry basis) (Henningsson, 1977), temperatures between 15 and 60°C and sufficient oxygen (Ernston et al., 1988; Everard et al., 2014). Not all fungi, however, thrive across the whole temperature range. Different temperature regimes favour different types of fungi with blue-stain typically favouring temperatures between 22-28°C; thermophilic moulds favouring temperatures between 45-55°C; and the rot fungi, which are the most crucial to dry matter losses, reach their optimum growth at around 25 to 32°C (Jirjis, 1988). As described in a review by Schwarze (2007) the three main types of wood-rotting fungi consume different parts of the wood, while white rot fungi mainly consume lignin but will also consume hemicellulose and cellulose in lesser amounts, and brown rot and soft rot fungi typically leave the lignin components intact but consume carbohydrates. This could be beneficial for optimizing the energy density of wood-chips as lignin has a higher energy content than carbohydrates. In addition to the chemical changes fungi and moulds can cause to the substrate, they can also be harmful to the workers handling the material after storage (Sebastian et al., 2006). Due to the negative consequences fungal propagation can have, methods for optimizing temperature and moisture content of wood-chip storage are incredibly valuable. Fungi are not, however, the only source of heat in a wood-chip pile, since, when a tree is chipped, the cells do not immediately die. The parenchyma in the tree thus continue to live, and will consume the left-over sugars remaining in the tree and respire (Armstrong, 1973; Kubler, 1990). This cellular respiration produces heat until the sugars are depleted and the cells die, given that the temperatures are suitable for cellular respiration (Saveyn et al., 2008).

A second source of energy generation, or perhaps of the movement of energy through a biomass pile, are the simultaneous evaporation and condensation processes. The movement of water can transfer heat throughout the pile with evaporative processes removing energy from the biomass and condensation adding energy to it (Ernston et al., 1988). This process typically works to equalize the hot and cold regions of the pile and will balance out the total heat in the pile. Walker & Harrison (1960), described by Armstrong (1973), outlines some additional effects of this process. Firstly, water can affect the thermal diffusivity and, above 60°C, it can cause a drop in the thermal conductivity of the pile, causing it to retain more heat. Secondly, redistribution of the water in the pile can leave the central areas drier and lacking the ability to dissipate heat through evaporation. Lastly, they outline the risk of heat being generated when water is absorbed by dry hydroscopic materials.

The last major source of heat generation is thermo-oxidative reactions, where, just as the parenchyma will react to being exposed to oxygen, so too will the chemical constituents of the wood.
The chemicals within the wood will oxidize and produce heat (Ernston et al., 1988). This reaction works past the temperature thresholds that usually halts micro-organisms’ metabolisms and works to push piles towards self-ignition (Springer et al., 1971). Given the complexity and number of different mechanisms that can drive pile self-heating, recreating these dynamic processes with an interactive model can help in understanding the differences between storing bark and wood.

1.4 Effects of Storage on Chip Quality and Temperature

While storage can present a problem, it is integral for managing seasonal demands, maintaining supply, and improving wood-chip quality. Moisture content plays a key role in the quality and price of biomass (Bedane et al., 2011), which can greatly affect its suitability as fuel. This presents itself in several different ways. Firstly, higher moisture content reduces the net heating value of the fuel (Tumuluru et al., 2011). This occurs because the energy released from the combustion reaction is consumed by the water to initiate evaporation. Higher moisture content also increases the cost of transportation by increasing the weight of residues (Nurmi, 1999), which results in energy producers paying extra fees for a substance which negatively impacts their fuel quality. Furthermore, high moisture content makes grinding more difficult, which can slow down processing (Tumuluru et al., 2011). The issue of increased temperatures and microbial invasions are likewise both related to high moisture content (Ernston et al., 1991), therefore minimizing the moisture is crucial. Water exists in three different states in wood: bound water, which is water within the cell walls of the wood; free water, which is water held in the cell cavities, or lumen; and water vapour (Souza et al., 2000). High moisture content presents a risk to self-heating as it allows microbes to degrade the wood and proliferate. Fungi and other microbes do this by using enzymes to break down wood cell walls so that they can feed on lignin and carbohydrates (Ernston et al., 1988).

Storage regimes and particle size play a crucial role in the quality and safety of wood-chip piles, since they can affect the moisture content, fungal susceptibility, pile temperature and, ultimately, fuel quality (Jirjis, 2005). A study referenced by Thörmqvist (1985) found that smaller residue piles stored for 6 months saw an increase in energy content due to decreases in moisture content and a lower dry matter loss rate, whereas larger piles stored for the same time saw an energy content decrease, due to a redistribution of moisture and a higher dry matter loss rate. This was also found by Gejdos et al. (2015) who found a 1 m tall pile had an increase in higher heating value while a 3 m pile had a decrease and, conversely, moisture content increased in the 3 m piles while it decreased in the 1 m pile.

In addition to pile size, particle size can cause profound quality changes, e.g., smaller particle size typically has a deleterious effect on quality, with higher dry matter and energy content loss (Pari et
al., 2015). Comparisons between wood-chips and chunks have found that quality after storage is highly dependent on particle size. It was found that chunks dry faster during the summer season than chips (Nurmi, 1988). When compared to chunks, chips were also found to have higher dry matter losses and higher concentrations of spores and dust (Gjølsjø, 1988; Jirjis, 1995). The benefits of particle size on moisture content and energy content reductions were mitigated when both piles were covered (Mitchell et al., 1988). Covering storage piles is typically beneficial with decreases in moisture contents being reported (Gjølsjø, 1988; Mitchell et al., 1988); this is mainly due to the prevention of rewetting from precipitation.

Compaction, which can increase a pile’s bulk density, also plays an important role in self-heating as higher rates of compaction have been correlated with higher temperatures (Jirjis et al, 1990). Temperature is generally uneven through the piles, and Nurmi (1999) found that temperature increase was highest on the outer portion of the pile. Furthermore, wood-chips, which typically have a higher bulk density, reached higher temperatures (20 °C higher than ambient temperature) than chunks (which remained around ambient temperature). This correlates with experimental data from Ferrero et al. (2009) who found that the internal temperature of a sawdust pile reached approximately 70° C whereas a wood-chip pile only reached 50° C. The low thermal conductivity of woody materials is problematic as heat produced within the pile is released slowly and therefore accumulates and pushes the pile closer to self-ignition (Ferrero et al., 2009).

Additionally, variations from seasonality can have an impact on wood quality during storage. Colder temperatures have an impact on the efficiency of drying, with the observed moisture contents in some studies indicating that wood chunks stored over the winter months had little decrease in moisture when their temperature remained around the cool ambient temperatures, with some piles even increasing in moisture content. Chip piles which could generate their own heat saw significant moisture decreases, as they were less reliant on warm ambient conditions driving their drying (Jirjis, 2005; Nurmi & Hillebrand., 2007). Conversely, Pettersson & Nordfjell (2007) noted that warmer ambient temperatures and summer vapour pressure deficits during the summer months in temperate climates were the most optimal time for drying stored biomass.

Some researchers have looked at methods to ventilate piles in order to reduce temperatures and moisture content which have had mixed results. Jirjis (1995) found that ventilation of wood-chip piles increased fungi content by reducing the internal temperature to levels preferred by fungi. Additionally, a covered chunk pile ventilated with vertical pipes had the same moisture content as a non-ventilated covered chunk pile (Arola et al., 1988), meaning that the large particle size was sufficient
to ventilate the pile on its own. It is evident that the techniques and setting for the storage of woody materials can have a tremendous impact on the quality of the material after its storage period, and as such should always be considered in order to avoid a decrease in chip quality.

1.5 Wood Pile Models

With so many different conditions affecting the overall energy content, fuel quality, and internal temperature of wood-chip residues stored in piles, there have been many efforts to simplify the processes into models. Kipping et al. (1988) looked at methods for optimizing wood-chip piles dried through the use of a forced air drier. They composed a model that looked at particle geometry, relative humidity, temperature and air-flow through the pile and hoped to optimize energy usage for drying in order to avoid the deleterious effects of chips above fibre saturation point. The model was not experimentally verified.

Mass transfer and heat movement have been investigated, as well. The goal of these models is to look at how water and volatile elements move throughout chip piles. Souza et al. (2000) produced a one-dimensional model which looked at how water moves through a pile through the diffusion of water vapour (which transfers heat), capillary action, diffusion of free water, heat conductivity and evaporation/condensation. The model therefore gives a moisture content loss dependant on temperature. Dedic et al. (2003) investigates the same mechanics with a three-dimensional model that estimates temperature and moisture content using a number of constants, with the focus being on drying the piles as quickly as possible in order to reduce fungal degradation resulting from high moisture content. Both of the models have their limitations as they use some experimental data, but rely heavily on non-dimensional numbers. While they are useful for conceptualizing the movement of water through the piles in three different phases, they fail to account for effects of fungi on the wood.

Ernstton et al. (1988) attempted to model heat and mass transport and reactions in wood piles with more accuracy. The one-dimensional model looked at the movement of heat, water and gases through the pile. The degradation reactions were then calculated based on the moisture content, heat and oxygen in the piles. The degradation constants had to be calculated experimentally and many simplifications were made, such as heat loss from the pile, assuming the pile was in a constant and optimal state for degradation and not taking into account the peak temperatures that occur when the temperature is adjusting from its initial temperature to its steady state temperature. The model mainly gives temperature and oxygen concentration results. The model was not experimentally verified.

Ferrero et al. (2009) produced a sophisticated two-dimensional model that focuses on temperature output as a predictor for pile auto-ignition. The model looks at conductive heat transfer
and heat transfer by diffusion, chemical concentrations and diffusivity, mass transport and the heat
generation of microorganisms. A model from Tremier et al. (2005) was incorporated in order to predict
the degradation of the easily and slowly degradable fractions of biomass and growth of fungi. The heat
effect of microorganisms is estimated using values from the wheat fungi studies of Koutinas et al. (2003)
and Von Strockar (1989). The study was experimentally verified using sawdust piles and wood-chip piles,
and mostly conformed to the temperature profiles. Ferrero et al.’s model has also been adapted to
other feedstock types; Everard et al. (2014) recently adapted the model to predict the auto-ignition risk
of miscanthus chip piles. They used a simplified version of the model which left out the microbial
temperature generation, which was justified by strictly examining the pile’s critical temperature, which
they defined as the point at which, even though the biological processes stopped generating heat, the
chemical and physical self-heating mechanisms of the pile would still be able to push the pile to self-
ignition. If the temperature was past 80°C then the pile was at low risk for self-ignition, since fungal
processes cease around this temperature. So, while it was not able to accurately predict internal
temperatures throughout the trial, it was able to conservatively estimate peak temperatures to avoid
auto-ignition. The drawbacks of the model are that it relies on many estimated parameters and that it
uses a static moisture content.

Seng et al. (2012) produced a moisture content model for compost piles which looks at the
moisture content of vertical columns throughout the pile. This model was verified using wood-chips so it
could, therefore, be adapted to bark moisture prediction. The model itself, however, relies on a static
temperature for its predictions. Bedane et al. (2011) produced a simple two-dimensional model that
predicts the temperature and moisture content of wood-chip piles and bundles based on ambient
weather conditions. The model uses physical wood properties and mass transfer constants to determine
the temperature and while it was simple the model closely simulated the internal temperature for the 3
m tall chip pile. The temperature predictions for the chip pile, however, were below the actual
observations as it did not take into account biological and chemical heat generation.

From the literature review it is evident that forest residue piles are complex systems with many
inputs. The fuel quality and self-ignition risk of the material can be affected by feedstock type, particle
size, pile dimensions, ambient conditions, covering and moisture content. Research on the storage of
pure bark piles is still limited and while utilizing wood-chip pile research is key to understanding bark
pile dynamics, determining their exact nature and differences requires further research which can be
performed by a model adapted for the properties of bark.
1.6 The Model

The Self-Heating Model created by Ferrero et al. (2009) will be used to simulate the self-ignition risk of the large bark pile. The model operates on three assumptions:

- Heat can be transferred between bulk material through conduction and diffusion
- Convection is accounted for by increasing the diffusion coefficients
- Material properties are independent of time and temperature

The model uses 17 separate equations to determine the temperature, the nomenclature for them can be found in Table 3.

The first equation is a Fourier equation, which uses the heat production value solved by the other equations to predict the temperature. The second equation sums up the heat production of the chemical, physical and microbiological fractions of the pile to get the total heat production. Equation 3 is a Fick equation which solves for the concentrations of different substances in the pile. Equation 4 is a convective heat flux equation which calculates the heat lost from the pile.

\[ \frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot C_p} \cdot \text{div} \ \text{grad} \ T + S_T \]  

\[ S_T = S_{T\text{Chemical}} + S_{T\text{Physical}} + S_{T\text{Microbiological}} \]  

\[ \frac{\partial C_k}{\partial t} = D_k \cdot \text{div} \ \text{grad} \ C_k + S_{C_k} \]  

\[ \dot{q} = \alpha \cdot (T_{amb} - T) \]
### Table 3: Nomenclature for self-heating model equations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>Area</td>
<td>m²</td>
<td>( RH )</td>
<td>Relative Humidity</td>
<td>-</td>
</tr>
<tr>
<td>( b )</td>
<td>Biomass death rate constant</td>
<td>s⁻¹</td>
<td>( S_{ck} )</td>
<td>Conversion rate of species, ( k )</td>
<td>kg/m³ s</td>
</tr>
<tr>
<td>( C_k )</td>
<td>Concentration of chemical species, ( k )</td>
<td>kg/m³</td>
<td>( S_T )</td>
<td>Total heat production</td>
<td>W/m³</td>
</tr>
<tr>
<td>( CD )</td>
<td>Condensation/adsorption constant</td>
<td>s⁻¹</td>
<td>( S_v )</td>
<td>Evaporation rate of liquid water</td>
<td>kg/m³ s</td>
</tr>
<tr>
<td>( C_p )</td>
<td>Specific heat of wood</td>
<td>J/kg K</td>
<td>( S_w )</td>
<td>Condensation rate of water vapor</td>
<td>kg/m³ s</td>
</tr>
<tr>
<td>( D_k )</td>
<td>Diffusion constant of gas species, ( k )</td>
<td>m²/s</td>
<td>( t )</td>
<td>Time</td>
<td>s</td>
</tr>
<tr>
<td>( E )</td>
<td>Activation energy</td>
<td>J/mol</td>
<td>( T )</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>( EV )</td>
<td>Evaporation/desorption constant</td>
<td>s⁻¹</td>
<td>( T_{amb} )</td>
<td>Ambient temperature</td>
<td>K</td>
</tr>
<tr>
<td>( f )</td>
<td>Fraction of dead biomass converted to inert</td>
<td>-</td>
<td>( v_k )</td>
<td>Stoichiometric coefficient of species, ( k )</td>
<td>-</td>
</tr>
<tr>
<td>( k_0 )</td>
<td>Pre-exponential factor</td>
<td>s⁻¹</td>
<td>( V )</td>
<td>Volume</td>
<td>m³</td>
</tr>
<tr>
<td>( K_b )</td>
<td>Substrate saturation constant for MB</td>
<td>kg/m³</td>
<td>( X )</td>
<td>Biomass concentration</td>
<td>kg/m³</td>
</tr>
<tr>
<td>( K_h )</td>
<td>Hydrolysis constant</td>
<td>s⁻¹</td>
<td>( Y )</td>
<td>Biomass yield on MB</td>
<td>-</td>
</tr>
<tr>
<td>( K_{MH} )</td>
<td>Substrate saturation constant for MH/X</td>
<td>-</td>
<td>( Y_{CO2} )</td>
<td>Biomass yield on CO₂</td>
<td>-</td>
</tr>
<tr>
<td>( M_k )</td>
<td>Molecular weight of species, ( k )</td>
<td>kg/mol</td>
<td>( \alpha )</td>
<td>Heat transfer coefficient</td>
<td>W/m² K</td>
</tr>
<tr>
<td>( MB )</td>
<td>Easily degradable fraction of biomass</td>
<td>kg/m³</td>
<td>( \Delta H_R )</td>
<td>Calorific value of wood</td>
<td>J/kg</td>
</tr>
<tr>
<td>( MC )</td>
<td>Moisture content</td>
<td>-</td>
<td>( \Delta H_v )</td>
<td>Water evaporation enthalpy</td>
<td>J/kg</td>
</tr>
<tr>
<td>( MH )</td>
<td>Slowly degradable fraction of biomass</td>
<td>kg/m³</td>
<td>( \lambda )</td>
<td>Wood thermal conductivity</td>
<td>W/m K</td>
</tr>
<tr>
<td>( q )</td>
<td>Convective heat flux</td>
<td>J/m² K</td>
<td>( \mu_m )</td>
<td>Biomass growth constant</td>
<td>s⁻¹</td>
</tr>
<tr>
<td>( q_{O2} )</td>
<td>Oxycaloric constant</td>
<td>J/kg</td>
<td>( \rho )</td>
<td>Density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>( R )</td>
<td>Universal gas constant</td>
<td>J/mol K</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Equations 5 through 8 work to determine the chemical concentrations of the pile as it changes, and then determine the heat production from their reactions. Equation 5 is a chemical reaction equation, used to represent the oxidation of biomass (CHO) into CO, CO₂, CH₄ and H₂O. Equation 6 is an Arrhenius equation that determines the conversion rate of biomass which is dependent on temperature and fuel concentration. Equation 7 is a conversion rate formula for the products of Equation 4. Equation 8 is an enthalpy equation used for calculating the heat produced by the chemical reactions of the pile.

\[ v_{Fuel}C_xH_yO_z + v_1O_2 \rightarrow v_2CO_2 + v_3CO + v_4CH_4 + v_5H_2O \]  \hspace{1cm} (5)

\[ S_{Fuel} = -C_{Fuel} \cdot k_0 \cdot \exp\left(-\frac{E}{R \cdot T}\right) \]  \hspace{1cm} (6)

\[ S_{C_k} = \frac{v_k}{v_{Fuel}} \cdot \frac{M_k}{M_{Fuel}} S_{Fuel} \]  \hspace{1cm} (7)

\[ S_{T_{chemical}} = -\frac{1}{\rho \cdot C_p} \Delta H_R S_{Fuel} \]  \hspace{1cm} (8)

Equations 9 through 11 examine heat and mass transfer throughout the pile. Equation 9 calculates the evaporation rate of liquid water in the pile in order to determine the amount of water vapor in the biomass. Equation 10 is used to account for the heat gained from condensation of water vapor, it is solved by converting the product of Equation 8 into a negative value. Equation 11 is used to calculate the temperature change of the pile as a result of the movement of water. It is a product of the heat required to vaporize water and the evaporation rate of the pile.

\[ S_w = EV \cdot C_w \cdot \exp\left(-\frac{\Delta H_v \cdot M_{H_2O, liquid}/1000}{R \cdot T}\right) + CD \cdot C_v \]  \hspace{1cm} (9)

\[ S_v = -S_w \]  \hspace{1cm} (10)

\[ S_{T_{physical}} = S_w \cdot \Delta H_v \]  \hspace{1cm} (11)
Equations 12 through 17 deal with the heat generation of the microorganisms in the pile. Equations 12 through 15 are based on a model produced from Tremier et al. (2005) which was adapted by Ferrero et al. (2009). Equation 12 estimates the amount of microorganisms in the pile based on factors like microbiological growth rate, death rate and the concentration of easily degradable biomass which are required for their growth. Equation 13 is used to calculate the slowly-degradable fraction of biomass that is converted to easily-degradable biomass through enzymatic hydrolysis. Equation 14 estimates the amount of easily-biodegradable biomass in the pile based on microbial growth and slowly-degradable biomass conversion through enzymatic hydrolysis. Equation 15 is the consumption of oxygen by microorganisms as oxygen is required by the microorganisms in order to consume biomass.

\[ S_X = \mu_m \frac{MB}{K_b + MB} X - b_X \]  

(12)

\[ S_{MH} = -K_h \frac{MH/X}{K_{MH} + MH/X} X \]  

(13)

\[ S_{MB} = -\frac{1}{Y} \mu_m \frac{MB}{K_b + MB} X + -K_h \frac{MH/X}{K_{MH} + MH/X} X \]  

(14)

\[ S_{O_2} = \frac{1 - Y}{Y} \mu_m \frac{MB}{K_b + MB} X + b(1 - f)X \]  

(15)

Equation 16 is the amount of carbon dioxide produced by microorganisms growing in the biomass pile. Finally, Equation 17 calculates the heat produced by microorganisms in the pile.

\[ S_{CO_2} = Y_{CO_2} \mu_m \frac{MB}{K_b + MB} X \]  

(16)

\[ S_{T_{Microbiological}} = S_{O_2} \cdot q_{O_2} \]  

(17)

2. Statement of Problem

Extensive research has been conducted in the field of wood storage; it has examined the energy content and potential of different forest feedstocks, the degradation of wood from fungal invasion, the effect of different levels of moisture content on fuel quality, and the effects of different storage settings on feedstock piles. Models have been produced by different researchers for simulating pile
temperatures, moisture content and energy losses in order to better understand the pile dynamics. Many of these models are built on mixed residues or pure whitewood and, while it is a common energy feedstock, not all energy production units use whitewood. One area of deficiency with these models is that they do not consider bark as a raw material (Filbakk et al., 2011).

Therefore, while models may be used for the optimization of pure whitewood piles or whitewood-dominated piles, they may produce inaccurate predictions for bark piles, and optimization techniques applied to whitewood piles may not be optimal for bark piles. Furthermore, Nova Scotia Power now requires the Port Hawkesbury biomass boiler to be run on demand. Ensuring the storage of the boiler’s bark feedstock is optimized, safe and efficient is, therefore, integral to meeting those demands. Consequently, further research is required in order to determine versatility and compatibility of wood-pile models for bark.

3. Purpose of Study

The intent of this study is to adapt the biomass self-heating model for the simulation and testing of a large bark pile. This will be carried out by setting up large-scale piles, monitoring their internal temperatures and characterizing the biomass to adapt the Ferrero (2009) model for the bark-dominated pile. The accuracy of the bark self-heating model will be determined through verification with the temperature data obtained from the large-scale experiments. Simulations will be done to gauge the importance of various parameters of the pile on self-heating. These parameters include:

- Size of the pile
- Bulk Density of the Pile
- Ambient weather conditions
- Thermal Conductivity

4. Hypotheses

- The physical parameters obtained from the characterization tests of actual stored bark material will predict the observed temperature in the large-scale tests more accurately than the wood parameters in Ferrero's self-heating model due to the physical differences between the two substrates,
- The effect of microbial heat generation can be simplified into constant values from Ferrero’s work instead of values that have to be obtained new for each pile being simulated due to the small variation in the variables associated with microbial degradation.
5. Significance

This research can contribute a valuable addition to the understanding of self-heating piles, since an accurate bark pile model would provide opportunities to test different bark pile setups without having to run long trials; this would, in-turn, allow Port Hawkesbury to optimize the characteristics of their bark piles to reduce the risk of self-ignition. It would also allow the company to understand the thresholds they can approach for drying the bark piles quickly, and allow them to reduce dry matter loss and save money on energy production in an industry which already has tight profit margins.

Furthermore, no simulations of heat generation in predominately bark piles have been conducted. Until now, only wood-chips or mixed residue piles have been modelled, so the present simulation will be the first of its kind and will help in identifying the unique characteristics of bark and how storage techniques used for pure wood-chips may be adjusted when applied to bark.

6. Methodology

6.1 Materials

The feedstock used in this trial was composed of mostly softwood bark and was obtained from local sawmills from the Cape Breton area, Irving Lumber, Scotsburn Lumber and Ledgewidge Lumber; bark was also obtained from the Bear Head legacy pile. Material was transported as chips to the storage site and material was screened through a Model 628 Trommel Screener and reground with a Model 4700B Peterson Horizontal Grinder, in order to ensure it met the boiler’s particle size requirements. Size data from FPInnovations indicated that the majority of the particles were under 22.2 mm in size, with 22% being under 3 mm, 27% being between 3 to 9.5 mm, 20% being between 9.5 to 15.9 mm, 22% being between 15.9 to 22.2 mm, 6% being between 22.2 to 44.5 mm and 3% being over 44.5 mm. Figure 2 shows a sample of the material that was used to build the piles.
6.2. Experiment Site

6.2.1 Port Hawkesbury Paper
The Port Hawkesbury Paper Mill is the second largest paper mill in the world. Its prior owners, Stora Kopparburg, opened the mill in the 1960’s and later added a biomass boiler to the facility so that it could generate its own power (Source: Mike Kelly, Nova Scotia Power). The boiler has a 60 MW capacity, with a 150 metric tonne steam turbine and consumes approximately 34 ODt of biomass per hour (Nova Scotia Power, 2013). In 2012, the paper mill was sold to the Stern Group (CBC, 2015), with the boiler being purchased by Nova Scotia Power (NSP). NSP stores forest residues on-site to be used in the NSP boiler to power Port Hawkesbury Paper (PHP) and, as of 2013, supplied 4% of Nova Scotia’s total electricity needs (Nova Scotia Power, 2013).

![Figure 2: Photo taken on-site of the material waiting to be piled](image)

The boiler at NSP was designed to run on a mixture of fuel primarily composed of bark, with 80% of the mix being bark supplied by pulp-log bark, and bark imported from throughout the local area. The remaining mixture of fuel is composed of white-wood and pulp sludge, with these ratios varying depending on the moisture content of the mixture. Moisture content is a critical parameter for the fuel
because when it is too high, power generation is impeded and when it is too low the temperatures of the boiler can exceed safe operating limits (Kelly, 2015).

In order to ensure a constant supply of bark for the boiler, large bark piles have been built around the PHP worksite. The site manager, related past incidents of noticeable sparking occurring on these piles, resulting in equipment having to be pulled away from them in case they spontaneously combusted (Holmes, 2015).

6.2.2 Trial Site
The site consisted of two large bark piles. The control pile which measured approximately 84 metres long, 25 m wide and 6.5 m tall, and was built during the week of November 2nd, 2015 and the aerated piped-pile which measured approximately 74 m long, 29 m wide and 6.5 m tall, and contained a 1 m diameter corrugated high-density polyethylene (HDPE) culvert pipe running its length. This pile was built from November 9th to 12th. Both piles were also covered by HDPE woven tarps, with small pipes running underneath in order to aid in air circulation (Holmes, 2015).

The piles are located on the Port Hawkesbury Paper grounds along a cliff edge. The grounds are located along the southern shore of Cape Breton Island. The piles are oriented approximately lengthwise, East-West, with their sides facing North-South. The non-piped pile was stored from its foundation in early November 2015 until the end of May 2016. The piped pile was stored from its foundation in November 2015 until the end of February 2016 when it was taken apart.

6.3 Large-scale Trials
In order to measure the internal temperature of the pile, Tinytag Talk 2 data loggers, fitted with waterproof cases, were utilized since they provide continuous measurements of the temperature. Temperature probes were pre-programmed and started prior to the trip so that they were ready for burial. In total, 30 probes were buried within the pile. After a location in the pile was selected, an excavator dug a hole for the probe. The probe was then placed in a 40L sand bag filled with bark and then sealed and buried. Ropes were attached to the probe bags and then tied to anchors surrounding the pile, so that the probes could be found and their data obtained. Samples were also collected in impermeable plastic bags at each location for the initial material analysis. Two probes were placed at both of the mouths of the pipe in the piped pile; they were placed in the sand bags, but were not filled with bark.

The approximate locations of the probes can be seen in Figure 3, with five probes being placed in the bottom of each pile, approximately 1 - 2 m off the ground, then 5 probes being placed around the middle of the pile, approximately 4 m off the ground, and then 5 probes being placed near the top of the
pile, approximately 5.5 m off the ground. There were limitations to distributing the probes evenly throughout the pile. First, the control pile was already built before the temperature probes were buried within, and the southern edge of the pile was along a cliff, making that side unreachable by the excavators. To compensate for this the excavators dug as deep as possible towards the centre of the pile, however the exact centre could not be reached, so the probes are concentrated along the northern side of the pile.

![Figure 3: Left: front of pile, Right: side of pile. Above, temperature probe placement in the control pile. Below, temperature probe placement in the piped pile. Locations appear as diamonds, and pipe appears as dashed line](image)

Second, the piped pile presented obstacles due to the central location of the pipe. Attempts were made to correct this by sending the five bottom probes to the site manager prior to our arrival, which allowed him to bury them in the centre of the pile just below the pipe. Due to the pipe limiting the possibility of putting probes along the centre at mid-height, they were offset to the west side of the pile, and then the final five probes at the top of the pile were offset to the east side in order to get a somewhat equal distribution.

The samples collected in impermeable bags were taken to the scale-house to be tested for moisture content using a Metso MR Moisture Analyzer. Select bags were shipped to the University of Toronto to calculate parameters for the production of a simulated model to estimate the risk of self-ignition within the pile. Samples were stored in a cold room at 4°C until tested. Particle Size samples were also taken and sent to FPIinnovations in Montreal for Particle Size analysis. Volume measurements were also obtained (4, 735 Green Metric ton for pile 1). This was done by measuring length, height and width using a rangefinder, which measured the distance between the device and a marker.
6.4 Bark Characterization Methodology

6.4.1 Parameter Methodology Preamble

In order to conform the large bark piles from Port Hawkesbury to the Ferrero et al. (2009) model. It was necessary to determine the unique physical, and chemical properties of bark; as wood and bark have different thermal properties, which can cause different self-heating regimes and ultimately affect the accuracy of the model.

6.4.2 Moisture Content

Moisture content tests were performed to obtain oven-dry weight of the sample for calculation of the fuel concentration parameter. Tests were performed based on standard ASTM E871-82. Moisture free paper bags were weighed, and then filled with approximately 100 to 200 g of bark sample, then reweighed. Samples were dried in a forced air dryer at 103±2°C for 24 hours. Samples were removed from dryer and cooled for 5 minutes. Due to the size of the samples, they were cooled without a desiccant. Dry samples were weighed and the moisture content (wet basis) was calculated using the following formula:

$$Moisture\ Content\ (\text{wet\ basis}) = \frac{Weight\ of\ biomass\ as\ received}{Weight\ of\ biomass\ after\ oven\ drying} \times 100$$

6.4.3 Ash Content

Ash content tests were performed in order to determine the inorganic fraction of the bark for the calculation of the fuel density parameter. Ash content tests were performed according to the ASTM D1102 standard. Ground samples at 18 mesh were weighed into oven-dried ceramic crucibles and placed in the oven at 105±2°C and dried until constant weight. Weighing occurred every 3 hours after cooling samples in a desiccator until room temperature. Once samples were oven-dry, they were put into the muffler furnace and held for 1 hour at 250±°C. The temperature was then raised to 550°C and held for 6 hours. Furnace was then shutdown, and the door opened for 10 minutes to cool the samples. Samples were then moved to a desiccator to cool for an additional 10 minutes and then weighed. The ash content was determined with the following formula:

$$Ash\ Content\ (%) = \frac{Oven\ dry\ mass\ of\ sample - Mass\ after\ furnace\ heating}{Mass\ before\ furnace\ heating} \times 100$$
6.4.4 Green Weight Bulk Density

Bulk density was obtained in order to calculate the fuel density of the parameter for the model. This was done according to standard CEN/TS 15103:2006. Loose bulk bark sample were poured to the 2500 mL line of a large volumetric container then lightly dropped three times and refilled until the volume of the biomass no longer declined. The biomass was weighed and the green weight bulk density was calculated using the following equation:

\[
\text{Bulk Density (kg/m}^3\text{)} = \frac{\text{Mass of filled container} - \text{Mass of empty container}}{\text{Volume of container}}
\]

6.4.5 Elemental Analysis

Elemental Analysis was performed in order to determine the C, H, and N content, and molecular weight of the bark for the model. In accordance with CEN/TS 15104:2005, sample was ground to an 80 mesh size. Moisture content samples were then taken and 1g of sample was sealed and analyzed with a 2400 Series II CHNS/O System Elemental Analyzer. The machine works by combusting organic samples at a high temperature and using the gases generated to represent the elemental fractions, CO\(_2\) for carbon, H\(_2\)O for hydrogen and N\(_2\) for nitrogen. The values received from ANALEST were then used to calculate the elemental fractions.

6.4.6 Higher heating value (HHV) methodology

HHV testing was performed in order to determine differences in HHV between bark and wood for the model simulation. Tests were conducted using the standard CEN/TS 14918:2005. Samples are ground to 18 mesh, and moisture contents determined. The bomb calorimeter was calibrated using 2 benzoic acid pellet trials. Approximately 0.3 to 0.35 g was weighed into the holder and compressed. Ten centimetres of ignition wire was cut and weighed. The bomb was assembled with the sample holder, the ignition wire and 3 mL of distilled water. The oxygen line is then attached to the bomb and pressure was raised to 20 atm. The calorimeter was filled with 2000 mL of room temperature water and the bomb was then lowered in, and wires affixed. The stirrer was activated and the thermometer was inserted. The base calorimeter temperature was obtained by obtaining a constant water temperature, and then the bomb was fired. The temperature was recorded every minute until constant temperature was achieved. The calorimeter was shut off, and the bomb was removed, unsealed and the residual ignition wire was collected and weighed. The water was inspected for residues, because sample can fall out of the sample tray and skew the results. If the water was clear then the results were accepted. The calorific value is then calculated using the following formula, which was then corrected for sample moisture content and ash content:
\[
\text{Gross Calorific value } \left( \frac{J}{g} \right) = \text{Heat capacity of calorimeter } \left( \frac{J}{K} \right) \cdot \text{Observed temperature rise } (K) - \frac{\text{Quantity of wire } (cm) \cdot \text{Calorific value of wire } \left( \frac{J}{g} \right)}{\text{Oven dry mass of the sample } (g)}
\]

6.4.7 Thermogravimetric Analyzer

The thermogravimetric analyzer (TGA) was used in this study to determine the first-order activation energy, which is the energy required to initiate the reaction, and pre-exponential factor, which is reaction rate, of the bark for comparison with wood. The TGA does this by exposing a small amount of sample to an increasing heating rate and then measuring the change in weight of sample. The TGA was calibrated with the blank pan, then 10 mg of bark that had been ground to an 18 mesh was weighed into the pan. A procedure was programmed wherein the TGA would ramp to 105°C at a rate of 10°C/min. When it reached 105°C the temperature was held for 5 minutes to remove any moisture from the sample. After 5 minutes, the sample was then heated at 2, 5, 7, or 10°C/min, depending on the run until it reached 550°C. The test was then run, and the data was analyzed using the Ozawa/Flynn/Wall method to calculate the first order activation energy and pre-exponential factor according to Standard ASTM E1641-16

6.4.8 Free Sugar Methodology

A Free Sugar Test was conducted in order to determine the easily-degradable fraction parameter for the model. To do this a method was adapted from Taylor (1999). The method is a colorimetric method that changes the hue of a solution based on the concentration of sugars in a solution, which can be quantified using a Ultra-Violet spectrophotometer.

To do this, an extract was produced using a hot water extraction method. Three replicates of the extract were made for each bark sample, and three moisture contents were taken for each sample. Extracts were prepared by creating bark ‘teabags’, which was done by weighing approximately 1 g of ground 18 mesh bark into a kim wipe. The kim wipe was then folded and secured with string to ensure that it would not reopen. A 250 mL Erlenmeyer flasks were then weighed and filled with 100 mL of distilled water. The teabags were added to the flasks which brought a boil for 1 hour using hotplates. Distilled water was sprayed down the sides of the flasks to remove the condensate; the flasks were
frequently rotated to ensure equal heating for all flasks across the hot plate. After the extraction was complete the flasks were weighed in order to determine the remaining quantity of extract.

Colorimetric tests were then carried out by diluting 1 mL of extract with 20 mL of distilled water. 2mL of the diluted extract was then mixed with 1 mL of a 5% v/v phenol solution, and then 5 mL of concentrated sulphuric acid was added and mixed. The solution was left to colour for 30 minutes. D-Glucose standards were made with a ppm of 0, 5, 10, 25, 50, 75, and 100. Once the colouring was finished, the samples were then measured using the UV photospectrometer at the 480 nm wavelength (Taylor, 1999); the machine was calibrated with a 0 ppm d-Glucose standard as a blank. The d-Glucose standards were graphed in order to obtain a linear regression which was used to estimate the extract sugar contents.

6.5 Model Methodology

Comsol Multiphysics Version 5.2 was used to simulate the heating in the bark pile, Comsol works by allowing the user to create a geometry, apply a material property to it and then apply physics to this geometry in order to attempt to predict how processes will occur spatially and temporally.

6.5.1 Geometry

Ferrero et al. (2009) used a 2D model for the simulation of the pile heating, a 3D and 2D geometry were used for simulations and yielded very similar results, so a 2D geometry was utilized in order to improve the processing time of the model. The geometry was created using a belzier polygon, with the length and height based on changeable parameters. The polygon rests on a large rectangle geometry with a soil material applied to it, which can be seen in Figure 4.

![Comsol model geometry](image)

*Figure 4: Comsol model geometry, trapezoid on top is the bark pile-geometry while the rectangle at the bottom is a soil geometry.*
6.5.2 Physics

Heat Transfer

Equations 1, 2 and 4 are represented in the model through the Heat Transfer module on Comsol, this model represents the transfer of heat within an object and between objects, depending on their material properties. The module was set as a non-isothermal object, and boundary conditions were set up on the sides and top of the geometry in order to simulate the loss of heat from the pile. The bottoms and side of the soil geometry were set as thermal insulation boundaries. A Heat Source condition was added to the pile geometry so that the pile would generate heat. Thin layer boundary conditions were added to the top and sides of the pile and given HDPE properties to try and take into account the heat transfer effects of the tarping.

Variables

The equations for the model were set as variables within the model; limitations were set for the model to ensure that realistic scenarios occurred. These limitations included restricting wood fraction concentrations from going below 0, and canceling the activity of the biological heating source when the temperature became too hot for the micro-organisms to metabolize in real work scenarios.

Biological Heat Source

The biological heat source was set by using a General Form PDE physics node. These nodes are used for creating custom physics; this heat source was only applied to the pile geometry and not the soil. This module models the degradation of easily degradable wood components, the growth of microbes, the conversion of slowly degradable wood fraction to more easily-degradable fractions and the emissions of CO$_2$ and O$_2$. From the emissions of O$_2$, the pile estimates the heat generation of the microbes in the pile. The physics were set up with three variables: the easily degradable fraction, the slowly degradable fraction, and the biomass (which refers to microbes which consume the woody material). The Convection-Diffusion Equation node (which represents equation 3) was added to this physics, and the source term for each variable was set as Equations 12 through 15. Equations 16 and 17 were added into the variables section with the module variables linked to them.

Chemical Heat Source

The chemical heat source was set by using a General Form PDE physics node; this heat source was only applied to the pile geometry. This module models the consumption of O$_2$ and fuel, the conversion of fuel to gas, and how the oxidation of fuel creates heat. The physics was set up with five variables: the concentration of remaining fuel, the concentrations of O$_2$, CO$_2$, CO and CH$_4$. A Convection-
Diffusion Equation node (which represents equation 3) was added to this physics; a Dirichlet Boundary condition was added to this model with the concentrations of the gases in open air in order to ensure that the outward boundaries of the pile were always near the levels of fresh air. The fuel concentration source term was set as Equation 6 while the gas concentration source terms were based on Equation 7 which was repeated in the variable section for each gas. Equation 8 was added into the variables section with the module variables linked to it.

Physical Heat Source

The Physical heat source was set by using a General Form PDE physics node; this heat source was only applied to the pile geometry. This module models the evaporation and condensation of water in the pile and how this moves heat around the pile, and dissipates heat. The physics was set up with two variables: the concentration of liquid water and water vapour. A Convection-Diffusion Equation node (which represents equation 3) was added to this physics. The source terms for the concentrations were based on Equations 9 and 10, while Equation 11 was added into the variables section with the module variables linked to it.

6.5.3 Mesh and Solution

The meshing of the model was a pre-defined Finer General Physics mesh. The solution was a one-step time dependant solution. Maximum time was set as 8640000 seconds, which equals 100 days, and time-steps were 100000 seconds each, which equals approximately one day. A PARADISO solver was used for this model.

7. Results

7.1 Field Trial

7.1.1 Handling the data

Several of the initial 30 probes were damaged and malfunctioning by the end of the trial, but data was obtained from 17 probes; Table 4 explains the layout of the surviving probes for the piles. For predicting the overall average pile temperature, each of the surviving probes were averaged at each hour mark. This, however, creates some bias for the temperature because of the four out of the seven surviving probes in Pile 1 were from the middle section of the pile, while of five of the ten surviving probes in Pile 2 were from the bottom section of the pile. This means that there is some skewing from the data, with the middle and bottom sections of Piles 1 and 2, respectively, being more represented than the other sections. Equally weighted charts were calculated (Figures 5 & 6) whereby the average of
each section was obtained and then the averages of the three sections in each pile were averaged together. This resulted in Pile 2 appearing almost 10°C hotter at some points of the trial, and Pile 1 appearing slightly cooler overall. Equal weighting would have been the preferred method if the sections had a more homogenous heat distribution, however this was not the case. Figure 7 shows the standard deviation over time for the five probes in the middle section of Pile 2 at each hour mark. It is shown that over time the standard deviation varied substantially, with the spread in temperatures of the middle of Pile 2 ranging from 0.2°C to 11.7°C. Therefore in order to better represent the variation in temperature of the pile even amongst its different sections, the probes were individually averaged together.

Table 4: Probe count and temperatures of each pile section for both piles

<table>
<thead>
<tr>
<th>Section</th>
<th>Pile</th>
<th>Probe Count</th>
<th>Minimum Temperature</th>
<th>Maximum Temperature</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>1</td>
<td>2</td>
<td>19.04</td>
<td>64.12</td>
<td>19.04</td>
</tr>
<tr>
<td>Middle</td>
<td>1</td>
<td>4</td>
<td>10.96</td>
<td>82.58</td>
<td>10.67</td>
</tr>
<tr>
<td>Bottom</td>
<td>1</td>
<td>1</td>
<td>26.02</td>
<td>50.27</td>
<td>6.36</td>
</tr>
<tr>
<td>Top</td>
<td>2</td>
<td>2</td>
<td>3.55</td>
<td>86.00</td>
<td>20.22</td>
</tr>
<tr>
<td>Middle</td>
<td>2</td>
<td>3</td>
<td>24.41</td>
<td>75.65</td>
<td>11.76</td>
</tr>
<tr>
<td>Bottom</td>
<td>2</td>
<td>5</td>
<td>18.35</td>
<td>65.82</td>
<td>10.12</td>
</tr>
</tbody>
</table>

Figure 5: Pile 1 temperature when all sections are weighted equally
7.1.2 Temperature variation among pile sections

The temperatures among different pile sections were observed in order to examine how they compared to the model’s predictions. Figure 8, shows the variation in pile temperature at different
heights in Pile 1. The probes at different height sections were averaged in order to determine the average temperature for each height section. The top of the pile shows the most variation, with it rapidly heating up to approximately 60°C, and then losing heat for the rest of the period. The middle section of the pile shows a steep temperature increase for the pile to 68°C; however, after an initial small drop, the temperature shows a very slow decrease in temperature until the end of the trial, with the temperature staying between 45 and 60°C. The bottom section of the pile was much different, showing a delayed slower rise in temperature, and then remaining between 40 and 50°C until the end of the trial. A single-factor ANOVA was run on the temperature profiles of the sections of pile to determine if they were statistically similar; a critical F-value of 2.9 and an F-value of 2864.7 were obtained, which indicated that no sections of the pile were statistically similar.

![Figure 8: Average temperature of all probes for each Pile 1 section over time](image)

Figure 9 shows that Pile 2 was similar in its temperature variation, showing a delayed, but steep rise to 74°C for the top probes in the pile, before dropping in January. The middle section shows a steep rise in temperature to 61°C, followed by a slower rise in temperature to 70°C with little heat dissipation until the end of the trial. The bottom of the pile, was drastically different, showing no jumps in temperature, but a very slow and steady increase in temperature for the whole trial, reaching 59°C by the termination of the trial. A single-factor ANOVA was run used to determine if the temperature
profiles of each of the sections of the pile were statistically similar; a critical F-value of 2.9 and an F-value of 1116.3 were obtained, which indicated that no sections of the pile were statistically similar.

Figure 9: Average temperature of all probes for each Pile 2 section over time

7.2 Bark Parameters

In order to more accurately model heat generation in the biomass piles composed primarily of bark materials from softwood species harvested from the Cape Breton area, it was necessary to determine the differences between a wood pile and a bark pile using computer modeling. Certain bark parameters were required, so it was necessary to determine and justify which parameters would represent the greatest difference between the two substrates, with respect to the model. The following table presents the parameters which are used in the model.
Table 5: Summary of the values used for simulation the wood pile and the bark pile, with justifications as to why each parameters chosen. Parameters in green were changed to bark values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bark Value</th>
<th>Wood Value (Ferrero)</th>
<th>Unit</th>
<th>Description</th>
<th>Justification</th>
<th>Source (if not from tests)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>2.78E-05</td>
<td>2.78E-05</td>
<td>[s⁻¹]</td>
<td>Death rate</td>
<td>Kostov et al. (1991) suggests that bark and wood decompose in a similar manner, after initial quicker decomposition for wood. Allison &amp; Klein (1961) found on average that barks and woods decompose in the same manner. Therefore the constants for how the micro-organisms grow, thrive and die on the wood should suffice for the 'behaviour' of the bark.</td>
<td>Tremier et al. 2005</td>
</tr>
<tr>
<td>f</td>
<td>0.2</td>
<td>0.2</td>
<td>-</td>
<td>Dead to inert</td>
<td>Tremier et al. 2005</td>
<td></td>
</tr>
<tr>
<td>Kb</td>
<td>0.009317</td>
<td>0.009317</td>
<td>[kg/m³]</td>
<td>Substrate saturation constant</td>
<td>Tremier et al. 2005</td>
<td></td>
</tr>
<tr>
<td>Kh</td>
<td>4.50E-05</td>
<td>4.50E-05</td>
<td>[s⁻¹]</td>
<td>Hydrolysis constant</td>
<td>Tremier et al. 2005</td>
<td></td>
</tr>
<tr>
<td>KMH</td>
<td>6.5</td>
<td>6.5</td>
<td>[kg/m³]</td>
<td>Saturation constant for MH/X</td>
<td>Tremier et al. 2005</td>
<td></td>
</tr>
<tr>
<td>MB0</td>
<td>2.3</td>
<td>6.8</td>
<td>[kg/m³]</td>
<td>Easily degradable fraction</td>
<td>Calculated from water extractable content of bark</td>
<td></td>
</tr>
<tr>
<td>MH0</td>
<td>122</td>
<td>130</td>
<td>[kg/m³]</td>
<td>Slowly degradable fraction</td>
<td>Calculated from water extractable content of bark</td>
<td></td>
</tr>
<tr>
<td>qO2</td>
<td>62.5</td>
<td>62.5</td>
<td>[kJ/kg]</td>
<td>Oxycaloric value</td>
<td>Kostov et al. (1991) suggests that bark and wood decompose in a similar manner, after initial quicker decomposition for wood. Allison &amp; Klein (1961) found on average that barks and woods decompose in the same manner. Therefore the constants for how the micro-organisms grow, thrive and die on the wood should suffice for the 'behaviour' of the bark.</td>
<td>Tremier et al. 2005</td>
</tr>
<tr>
<td>um</td>
<td>7.09E-05</td>
<td>7.09E-05</td>
<td>[s⁻¹]</td>
<td>Biomass growth rate</td>
<td>Ferrero et al. 2009</td>
<td></td>
</tr>
<tr>
<td>X0</td>
<td>3.45E-02</td>
<td>3.45E-02</td>
<td>[kg/m³]</td>
<td>Biomass initial concentration</td>
<td>Tremier et al. 2005</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>0.68</td>
<td>0.68</td>
<td>-</td>
<td>Biomass yield on MB</td>
<td>Tremier et al. 2005</td>
<td></td>
</tr>
<tr>
<td>YCO2</td>
<td>1.79</td>
<td>1.79</td>
<td>-</td>
<td>Biomass yield on CO₂</td>
<td>Tremier et al. 2005</td>
<td></td>
</tr>
<tr>
<td>Chemistry</td>
<td>( CCH_4 )</td>
<td>0</td>
<td>0</td>
<td>([\text{kg/m}^3])</td>
<td>( \text{CH}_4 ) initial concentration</td>
<td>Ambient conditions for gases were not taken during the start of the trial, therefore assumptions have to be made</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>( CCO_2 )</td>
<td>0</td>
<td>0</td>
<td>([\text{kg/m}^3])</td>
<td>( \text{CO}_2 ) initial concentration</td>
<td>Assumptions from Ferrero model</td>
<td></td>
</tr>
<tr>
<td>( CCO )</td>
<td>0</td>
<td>0</td>
<td>([\text{kg/m}^3])</td>
<td>( \text{CO} ) initial concentration</td>
<td>Assumptions from Ferrero model</td>
<td></td>
</tr>
<tr>
<td>( C_fuel )</td>
<td>124.47</td>
<td>136</td>
<td>([\text{kg/m}^3])</td>
<td>Initial concentration of fuel</td>
<td>The fuel concentration will be different from Ferrero's model due to the differences in BD, MC and AC for our material</td>
<td>Calculated from BD, MC and AC tests</td>
</tr>
<tr>
<td>( CO_2 )</td>
<td>0.252</td>
<td>0.252</td>
<td>([\text{kg/m}^3])</td>
<td>Initial concentration of oxygen</td>
<td>Ambient conditions for gases were not taken during the start of the trial, therefore assumptions have to be made</td>
<td>Assumptions from Ferrero model</td>
</tr>
<tr>
<td>( dHR )</td>
<td>2.2E+07</td>
<td>2.01E+07</td>
<td>([\text{J/kg}])</td>
<td>Calorific Value</td>
<td>Biomass has similar calorific values in general, bark could be higher than wood though, due to its increased lignin content</td>
<td>Calculated from Caloric test</td>
</tr>
<tr>
<td>( dHv )</td>
<td>2.10E+06</td>
<td>2.10E+06</td>
<td>([\text{J/kg}])</td>
<td>Water enthalpy</td>
<td>Standard values</td>
<td>Ferrero et al. 2009</td>
</tr>
<tr>
<td>( D_k )</td>
<td>8.00E-03</td>
<td>8.00E-03</td>
<td>([\text{m}^2/\text{s}])</td>
<td>Gas diffusion</td>
<td>Coefficient value calculated by Ferrero</td>
<td>Ferrero et al. 2009</td>
</tr>
<tr>
<td>( ER )</td>
<td>11607</td>
<td>11607</td>
<td>([\text{K}])</td>
<td>Activation Energy/Gas Value</td>
<td>Testing was done in Comsol and increases in this factor did not yield significant changes to the temperature profile.</td>
<td>Ferrero et al. 2009</td>
</tr>
<tr>
<td>( k_0 )</td>
<td>9.64E+04</td>
<td>9.64E+04</td>
<td>([\text{s}^{-1}])</td>
<td>Pre-exponential factor</td>
<td>Testing was done in Comsol and increases in this factor did not yield significant changes to the temperature profile.</td>
<td>Ferrero et al. 2009</td>
</tr>
<tr>
<td>( M_{CH_4} )</td>
<td>0.016</td>
<td>0.016</td>
<td>([\text{kg/mol}])</td>
<td>Weight of ( \text{CH}_4 )</td>
<td>Standard values</td>
<td>Ferrero et al. 2009</td>
</tr>
<tr>
<td>( M_{CO} )</td>
<td>0.028</td>
<td>0.028</td>
<td>([\text{kg/mol}])</td>
<td>Weight of ( \text{CO} )</td>
<td>Standard values</td>
<td>Ferrero et al. 2009</td>
</tr>
<tr>
<td>( M_{CO_2} )</td>
<td>0.044</td>
<td>0.044</td>
<td>([\text{kg/mol}])</td>
<td>Weight of ( \text{CO}_2 )</td>
<td>Standard values</td>
<td>Ferrero et al. 2009</td>
</tr>
<tr>
<td>( M_{fuel} )</td>
<td>0.03</td>
<td>0.03</td>
<td>([\text{kg/mol}])</td>
<td>Molecular</td>
<td>Different balances of Lignin, Cellulose</td>
<td>CHNO Test</td>
</tr>
</tbody>
</table>
and Hemi-Cellulose could affect the molecular weight of the fuel, thus it was important to determine if this value would differ for bark.

<table>
<thead>
<tr>
<th></th>
<th>Weight of Fuel</th>
<th>Weight of Water vapour</th>
<th>Weight of Water liquid</th>
<th>Weight of O₂</th>
<th>Universal gas constant</th>
<th>Stoichiometric coefficient</th>
<th>Standard values</th>
<th>Ferrero et al. 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH20vap</td>
<td>0.018</td>
<td>0.018</td>
<td>[kg/mol]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MH2Oliq</td>
<td>0.018</td>
<td>0.018</td>
<td>[kg/mol]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MO2</td>
<td>0.032</td>
<td>0.032</td>
<td>[kg/mol]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>8.314</td>
<td>8.314</td>
<td>[J/mol K]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v1</td>
<td>-0.961</td>
<td>-0.961</td>
<td></td>
<td></td>
<td>O₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v2</td>
<td>0.79</td>
<td>0.79</td>
<td></td>
<td></td>
<td>CO₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v3</td>
<td>0.189</td>
<td>0.189</td>
<td></td>
<td></td>
<td>CO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v4</td>
<td>0.021</td>
<td>0.021</td>
<td></td>
<td></td>
<td>CH₄</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v5</td>
<td>0.812</td>
<td>0.812</td>
<td></td>
<td></td>
<td>H₂O vapour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vfuel</td>
<td>-1</td>
<td>-1</td>
<td></td>
<td></td>
<td>Fuel</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Physical and Ambient Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Unit</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>alpha</td>
<td>8</td>
<td>8</td>
<td>[W/m² K]</td>
<td>Heat Transfer coefficient</td>
<td>Coefficient value calculated by Ferrero specifically for model</td>
</tr>
<tr>
<td>Cp</td>
<td>1597.45</td>
<td>1350</td>
<td>[J/kg K]</td>
<td>Specific Heat Capacity</td>
<td>Thermal Conductivity and Specific Heat Capacity for Bark and Wood differ, with barks having a lower conductance and thus moving heat more slowly</td>
</tr>
<tr>
<td>CD</td>
<td>0.000027</td>
<td>0.000027</td>
<td>[s⁻¹]</td>
<td>Condensation</td>
<td>Coefficient value calculated by Ferrero</td>
</tr>
<tr>
<td>EV</td>
<td>0.015</td>
<td>0.015</td>
<td>[s⁻¹]</td>
<td>Evaporation</td>
<td>Coefficient value calculated by Ferrero</td>
</tr>
<tr>
<td>Lambda</td>
<td>0.064</td>
<td>0.188</td>
<td>[W/m²]</td>
<td>Thermal Conductivity</td>
<td>Thermal Conductivity and Specific Heat Capacity for Bark and Wood differ, with barks having a lower conductance and thus moving heat more slowly</td>
</tr>
<tr>
<td>MC0</td>
<td>0.51</td>
<td>0.35</td>
<td>-</td>
<td>Moisture content</td>
<td>Physical characteristic that differs for most piles</td>
</tr>
<tr>
<td>rho</td>
<td>305.58</td>
<td>210</td>
<td>[kg/m³]</td>
<td>Bulk density</td>
<td>Bulk density test</td>
</tr>
<tr>
<td>RH0</td>
<td>0.63</td>
<td>0.94</td>
<td>-</td>
<td>Relative Humidity</td>
<td>Standard values</td>
</tr>
<tr>
<td>T0</td>
<td>302</td>
<td>293</td>
<td>[K]</td>
<td>Initial bark temperature</td>
<td>Standard values</td>
</tr>
<tr>
<td>T0air</td>
<td>279.65</td>
<td>298.3</td>
<td>[K]</td>
<td>Initial air temperature</td>
<td>Standard values</td>
</tr>
</tbody>
</table>
Physical parameters were tested, as they impact heat retention and are important for quantifying the fuel content of the material in the pile. Moisture content was obtained from the bark samples; the average moisture content for the bark was 50.08%, with a standard deviation of 2.07%. Pile 1 had an average moisture content of 48.66% with a standard deviation of 2.39%, while Pile 2 had an average moisture content of 51.49% with a standard deviation of 1.75%. Furthermore a t-test obtained a P-value of 0.71 for an α-value of 0.05 indicating that these samples were statistically similar. The Bulk Density of loose sample was obtained for each pile; Pile 1 had a bulk density of 295 kg/m³ with a standard deviation of 25.78 kg/m³; Pile 2 had a bulk density of 277 kg/m³ with a standard deviation of 35.4 kg/m³, while the average of both was 286 kg/m³ with a standard deviation of 30.59 kg/m³; t-test results indicated a p-value of 0.18 for an α-value of 0.05 meaning that the samples were statistically similar. The results for the inorganic fraction of oven-dry bark indicated that there was an average inorganic fraction of 11.42% with a standard deviation of 3.08% for Pile 1. The value for Pile 2 was lower with an inorganic fraction of 9.92% with a standard deviation of 2.31%. The average inorganic fraction for both piles was 10.52% with a standard deviation of 2.74%; t-tests yielded a p-value of 0.37 for an α-value of 0.05 indicating that these samples were statistically similar.

The averages of the bulk density represent an uncompacted bulk density, so they do not take into account the increased density from the weight of the pile itself. In the model, a calculation was used which was prepared by Advanced Biomass Consulting Inc. to predict the impact of pile height on bulk density. This model estimates the increasing force of compaction from the biomass weighing down on its lower layers; it determined that the weight of the pile would increase bulk density to 305.58 kg/m³. The Fuel Concentration then calculated using the compacted bulk density value and removing the average moisture content and the inorganic fraction to get a value of 133.08 kg/m³. The easily degradable fraction was determined by estimating the sugar fraction of the bark based on a glucose standard. According to this methodology, the sugar fraction of Pile 1 was estimated to be 1.69%, while the sugar fraction of Pile 2 was 2.2%; t-tests yielded a p-value of 0.0004 for an α-value of 0.05 indicating that these piles were not statistically similar, so the respective pile average was used when modeling each pile.

Some chemical and kinetic factors for the bark were tested. A CHNO analysis was done on the bark, which determined the elemental composition of the bark. When corrected for ash-content and moisture content, the bark of Pile 1 had a Carbon, Hydrogen, Nitrogen and Oxygen content of 55.37%,
6.59%, 0.61% and 37.42%, respectively. The Carbon, Hydrogen, Nitrogen and Oxygen values for Pile 2 were 56.88%, 6.81%, 0.54% and 35.76%, respectively. The averages for the 2 piles were 56.12% for Carbon, 6.7% for Hydrogen, 0.57% for Nitrogen, and 36.59% for Oxygen. The Higher-Heating Value with the ash content removed for Pile 1 was 22.24 MJ/kg with a standard deviation of 2.07 MJ/kg, while for Pile 2, the value was 21.86 MJ/kg with a standard deviation of 1.22 MJ/kg. The average Higher Heating Value for the both piles was 22.05 MJ/kg with a standard deviation of 1.64 MJ/kg. Some thermal values were calculated using regressions from literature. The thermal conductivity of the piles was calculated using Equation 18 (below) from (Kain et al., 2013) and estimated a conductivity of 0.066 W/m². A model from Martin (1963) was used to calculate specific heat capacity which estimated a value of 1597.45 J/kg K for the bark from Equation 19 (below). The analysis using the Thermogravimetric analyzer yielded kinetic factors for a first-order reaction. Pile 1 had an activation energy of 133,873.2 J/mol with a pre-exponential factor of 4.92x10¹¹ min⁻¹. Pile 2 had an activation energy of 119,280.1 J/mol with a pre-exponential factor of 2.16x10¹⁰ min⁻¹.

\[ \text{Thermal Conductivity} = 1.08 \times 10^{-4} \times \text{Substrate Bulk Density} + 3.37 \times 10^{-2} \]  
\[ \text{Specific Heat Capacity} = 0.264 + 0.00116 \times \text{Temperature} + 0.083 \]

7.3 Model Results

The intention of obtaining certain bark parameters was to make a more accurate prediction of self-heating in bark piles. It is hypothesized that bark’s unique physical and chemical characteristics can change the generation and dissipation of heat. Figure 10 displays the results of the simulation using parameters derived for bark (light blue), wood physical parameters (dark blue) from the pile in Ferrero et al. (2009), and the average temperature of the pile in the real-world trial (green). Wood parameters used in the model were taken from Ferrero et al. (2009) because they were similar in particle size and fuel concentration to the bark examined in this study. The pile average for each pile was an average from all the surviving probes in the pile, with corrupt data points removed, a data point was determined to be corrupt if a sudden impossible jump occurred in the data timeline (i.e. a rapid temperature decline of 30°C). The graph shows an initial slow rise of temperature in the the bark pile, peaking at approximately 57°C with a slow loss in heat, as well as a slight increase in temperature at the 70-day mark following; at this point, however, the probes in the top and middle portions of the pile ceased functioning, so only those probes at the bottom of the pile were recording data. The simulation follows the slow rise in heat, peaking at approximately 53°C as well as the retention of heat. At the 70-day mark,
the two temperatures move in opposing directions. The wood simulation does not follow the pile temperature profile, as it more rapidly accumulates heat during the first 15 days, peaking at 50°C, and then steadily loses heat for the remaining period of the trial.

Figure 10: Average bark pile temperature compared to simulations with wood values and bark values

8. Discussion

8.1 Considerations

The biological heating source component of the model is one of the main drivers of energy generation in the pile. When reviewing the parameters that may be different between wood and bark, it was determined that the parameters used by Fabio et al. (2009) for the degradation of wood would be suitable for bark; Kostov et al. (1991) suggests that bark and wood decompose in a similar manner, with wood decomposing slightly quicker during the initial phases. Which was accounted for due to the increased easily degradable fraction in wood for the model. Furthermore, Allison & Klein (1961) found that on average softwood bark and wood decompose in the same manner, with some species bark decomposing more rapidly, and some more slowly. Since most of the material in the pile was derived from softwoods, it was assumed that the pile would decompose in a similar manner to wood, and that the smaller easily degradable fraction would account for the slower initial decomposition seen in Kostov et al. (1991). It is important to note, however, that, according to Allison & Murphy (1962), hardwood barks degrade slower than woods, so had the bark pile been derived from mostly hardwoods, new degradation parameters should be considered for the simulations, as this material could result in lower rates of self-heating, and lower quality losses.
The Ferrero et al. (2009) paper indicated that the activation energy and pre-exponential factor were based on a first-order reaction. When discussing the model with the author, he explained that the model actually required a zero-order reaction parameter. A zero-order reaction has a reaction rate that is independent of the concentration of the reactant, whereas a first-order reaction depends on the concentration of one substance, in this case being the fuel concentration of the wood. Therefore, for the purposes of comparing bark to wood, the first-order activation energy obtained through Thermo-gravimetric analysis was determined and used in the model. For the model, however, sensitivity analysis testing was done in order to determine that the differences in the activation energy did not differentiate the temperature profile of the model significantly (Figure 11), resulting in the two curves being almost identical. Furthermore, Lopez-Gonzalez & Lopez (2013) states that a zero-order reaction is independent of concentration and that the activation energy for bark and wood does not significantly differ. It was therefore decided that the zero-order activation energy obtained by Ferrero et al. (2009) would be used for simulating the bark pile.

![Figure 11: Sensitivity analysis of kinetic factors](image)

The evaporative and condensation constants and physical self-heating equations are from a model prepared by Lohrer et al. (2005) that looks at modeling the effects of condensation and evaporation for coal. The constants are exclusive to the Lohrer model. The condensation and evaporation constants from the Ferrero et al. (2009) model were determined using a different method from the Lohrer model, which was done by manually adjusting the coefficients until the simulated data
would match the real-trial data. A similar method was utilized for obtaining the parameters for the model in this study, i.e., by matching the simulated data to the real-trial results.

8.2 Bark Parameters

8.2.1 Basic Characteristics

As mentioned above, the bark collected from the piles has some key differences in characteristics compared to white wood. Some characteristics are innately different while others can be surmised as situational. Bulk density and moisture content are two characteristics that can differ based on many different factors, including the region of the site, collection time, storage length, material particle size, species and type of material, and pile shape (Laurilia & Lauhen, 2010; Jirjis, 2005; Ragland, et al., 1991). A study from Manwiller (1975) looked at moisture content in tree bark, and found that, among the hardwoods tested, six species had a higher stem bark moisture content than stem wood, while 14 species had a lower stem bark moisture content than stem wood. Therefore, given the differing feedstock types and storage setting for the bark in this study and the wood from Ferrero et al. (2009) it is reasonable that the moisture contents differ by nearly 15%. A study from Lehtikangas (2001) of fresh temperate pine and spruce bark forest residues and sawdust found most of the bark and sawdust to have a moisture content in the range of 50-60% wet basis. Had these feedstocks come from the same harvest and storage trial, the bark and wood would probably have been much more similar in their moisture content.

Bulk density between bark and wood can differ significantly; Table 6 displays the oven-dry weight of bark per volume of several softwood species found in Eastern Canada. These values show that bark and wood can vary significantly with their weights, with bark weighing more than wood for three of the species, and wood weighing more than bark for four of the species. On average the weights for these species are not significantly different with a t-test of these data returning a p-value of 0.62 for the α-value of 0.05. Furthermore, Wagenfuhr (1996) data reported by Krajnc (2015) gave the typical bulk density of coniferous bark as 205 kg/m³ and wood as 195 kg/m³, which differ only by 10 kg/m³. Therefore, within this context, it is consistent with literature that between the oven-dry bulk densities of the Ferrero et al. (2009) model wood and the bark used in this study there was only a difference of 8 kg/m³.
### Table 6: Oven dry weight of Eastern Canadian softwood bark and wood as reported by Miles & Smith (2009)

<table>
<thead>
<tr>
<th>Tree Species</th>
<th>Oven dry weight of bark (kg/m³)</th>
<th>Oven dry weight of wood (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balsam Fir</td>
<td>400</td>
<td>330</td>
</tr>
<tr>
<td>White Spruce</td>
<td>390</td>
<td>370</td>
</tr>
<tr>
<td>Black Spruce</td>
<td>420</td>
<td>380</td>
</tr>
<tr>
<td>Red Spruce</td>
<td>320</td>
<td>370</td>
</tr>
<tr>
<td>Eastern White Pine</td>
<td>270</td>
<td>410</td>
</tr>
<tr>
<td>Red Pine</td>
<td>470</td>
<td>340</td>
</tr>
<tr>
<td>Tamarack (<em>Larix laricina</em>)</td>
<td>300</td>
<td>490</td>
</tr>
<tr>
<td>Average</td>
<td>367</td>
<td>384</td>
</tr>
</tbody>
</table>

#### 8.2.2 Parameters That Differ From Wood

There are some key differences that will always differ between bark and wood, regardless of situation. The ash content of bark is typically much higher than wood. According to Fengel & Wegener (1984) quoted by Ragland et al. (1991), ash content for temperate trees is typically between 0.1 to 1.0% while barks can contain up to 3-8% ash. Lehtikangas (2001) looked at bark and sawdust and found similar results, with sawdust ash content being around 0.2% and bark ash content being between 2.65 and 6.94%. The values obtained for the bark in this study were fairly high, with the average of 12.89% and a range of 7 to 24%. These high values are likely the results of dirt from handling and dragging during harvesting and processing, as the bark was not pre-washed before any of the tests were conducted, Miranada et al. (2012) notes that pine bark is more prone to soil contamination due to their macroscopical structure.

The increased ash content of the bark can have different effects on the utilization of the bark. Firstly, due to the increased inorganic fraction, the fuel density of bark may be lower than its wood counterpart, for example the wood in Ferrero et al. (2009) had a dry weight of 136 kg/m³, while the dry uncompressed weight of the bark was 142.90 kg/m³, however, when the inorganic fraction is removed, the weight falls to 124.47 kg/m³, with the wood fraction staying roughly the same. The reduction in fuel density from high ash content is not the only issue. The kinetic factors for the material can be increased by higher ash content. A study from Jayanti & Saravanan (2007) on coal found that increased ash content in coal decreased the rate of combustion of the fuel, likely by reducing the diffusion of oxygen through the material. In addition to this, lower ash contents are preferred for combustion purposes for
logistical reasons, as high ash contents can negatively impact the handling and processing costs of wood fuels (McKendry, 2002).

The Activation Energy which was calculated for a First order reaction, is higher for bark when compared to wood, which is also seen in Lopez-Gonzalez & Lopez (2013) where softwood bark had a first order activation energy of 140 kJ/mol to 107 kJ/mol for softwood. Lopez-Gonzalez & Lopez state, however, that the overall reactivity of these lignocellulosic materials are similar and not significantly different. The same was observed in the sensitivity analysis carried out in this study which did not show a significant difference in pile temperature change when the activation energy was increased.

The fraction of easily-degradable matter, which is an approximation of materials, such as free sugars, that microbes will preferentially consume differed between bark and wood. The wood in Ferrero et al. (2009) had an easily degradable fraction of approximately 5%, whereas the bark in this study contained only 2.3% easily degradable fraction. This compares to literature with Norway spruce sapwood containing a sugar fraction of roughly 2.0 to 6.7% (Song et al. 2012) compared to a value of 1.8 to 2.3% for Norway spruce bark (Kemppainen et al., 2014). In the simulations, it was found that this difference in sugars resulted in a slower and steadier rise in temperature, which was also observed in the actual temperature monitoring data for Pile 2.

8.2.3 Parameters That Did Not Differ

Some of the values for the wood and bark did not significantly differ. The higher heating value obtained from the bark did not significantly differ from the wood; the bark in this study had a higher heating value of 22.05 MJ/kg while the Ferrero et al. (2009) wood was 20.1 MJ/kg. These values compare well with other values from literature. Lehtikangas (2001) found that fresh bark had a higher heating value of 20.14 MJ/kg and fresh sawdust a value of 20.15 MJ/kg. While Lehtikangas (2001) work did show the two substrates with similar heating values, typically bark will have a slightly higher heating value than wood. Data from Singh (1986), which looked at Manitoba species which were freshly harvested, dried and tested with a calorimeter, also showed that there were similarities in bark and wood higher heating values. Table 7 shows this, with all barks except for balsam fir having a similar but slightly greater higher heating than stem wood taken from the same tree. This is because bark contains more lignin than wood, with bark typically having a lignin content of 44.13% and spruce wood having a lignin content of 31.58% (Demirbas, 2001). This results in a higher heating rate because lignin has a greater higher heating value than cellulose, with an HHV of 23.26 to 25.58 MJ/kg for lignin and an HHV of 18.6 MJ/kg for cellulose (Howard, 1973). This difference in lignin results in only a slight increase in
HHV for bark. As bark and wood are both lignocellulosic materials, they have a similar chemical composition; Lamlor & Savidge (2003) found carbon contents of North American softwoods to be in the range of 47.21 to 55.16%, with hydrogen content being 7.63 to 8.74%. According to data described in Ragland (1991) pine bark had a carbon content of 54.9%. Hydrogen content of 5.8%, nitrogen content of 0.2% and an oxygen content of 39.0% which is close to the values for the bark in this study of 56.12%, 6.7%, 0.5% and 36.5%, respectively.

8.2.4 Modeled Thermal Parameters

Specific heat capacity and thermal conductivity were determined using a model for predicting specific heat capacity (Martin, 1963). The model predicts the specific heat capacity based on the temperature of the bark, the sorption of heat from water is then taken into account based on the bark’s moisture content. The model predicted a specific heat capacity of 1597.45 J/kg K which is comparable to the specific heat capacity of 1350 J/kg K used by Ferrero et al. (2009). Martin (1963) found that bark and wood are similar in their specific heat capacity.

Table 7: Higher heating values for bark and stem wood from 6 Eastern Canadian softwoods from Singh (1986)

<table>
<thead>
<tr>
<th>Species</th>
<th>Higher heating value of bark (MJ/kg)</th>
<th>Higher heating value of stem wood (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Spruce</td>
<td>19.830</td>
<td>19.018</td>
</tr>
<tr>
<td>Black Spruce</td>
<td>19.478</td>
<td>18.784</td>
</tr>
<tr>
<td>Jack Pine</td>
<td>21.299</td>
<td>19.443</td>
</tr>
<tr>
<td>Eastern White Cedar (Thuja occidentalis)</td>
<td>21.446</td>
<td>19.96</td>
</tr>
<tr>
<td>Tamarack</td>
<td>19.490</td>
<td>18.783</td>
</tr>
<tr>
<td>Balsam Fir</td>
<td>18.527</td>
<td>18.746</td>
</tr>
</tbody>
</table>

Thermal conductivity was determined using a regression model calculated by Kain et al. (2013), from which a value of 0.064 W/m K was derived. This value is in line with other values in literature, which were between 0.065 and 0.11 W/m K for European softwoods (Pasztory & Ronyecz, 2013). Ferrero et al. (2009) obtained a value of 0.18 W/m K, which is substantially more conductive than the bark. These values were comparable to bark and wood values found by Raznjevic (1976) which found values of 0.055 to 0.074 W/m K for bark and 0.128 to 0.186 W/m K for wood of a similar density.
8.3 Trial Discussion

8.3.1 Trial Setup and Results

There were some differences in the way the trial was conducted that may have affected the temperature profile of each pile. The first difference was the ventilation pipe installed in Pile 2; this pipe could have aerated the pile and resulted in a lower overall temperature. It was found in a study from Jirjis (1995) that when a ventilation system was added to a pile it decreased the temperature of the pile enough to allow for the increased activity of micro-organisms and an increase in their proliferation. It has been found in composting studies that temperatures in excess of 60°C can inhibit the microbial activity (Iannotti et al., 1993). There is a slight difference in pile height, with Pile 1 being 6.5 m tall and Pile 2 being 7.1 m tall, pile width was also similar with Pile 1 being approximately 25 m wide, with Pile 2 being 28 m wide. There was, however, a more pronounced difference in length, with Pile 1 being approximately 80 m long while Pile 2 was on average approximately 15 m shorter at 67 m long. This means there is a larger volume of material contained in Pile 1. While the pile heights only differ by 0.6 m, the sensitivity analysis did indicate that pile height affected the heat release of the pile, and Pile 2’s taller height could relate to the higher temperatures recorded by some of the probes in the pile.

There were also some differences in the pile set up. Pile 1 was built the week prior to the start of the trial, when the temperature probes were being set up, the pile was reopened and the probes were inserted. Pile 2 was set up during the start of the trial, with the probes being inserted into the pile as it was being built. This means there could be some disturbance in the initial temperature production and movement of Pile 1, and potentially more oxygen being added to the pile which could elevate microbial activity. This should be considered when looking at the temperature profile, as it could account for some of the temperature differences. Pile 1’s trial was also significantly longer than Pile 2’s trial, terminating in the beginning of May 2016 instead of February 2016 for Pile 2. This is likely the most important factor for why Pile 2 had a higher temperature than Pile 1. It is likely that when Pile 1 was reopened to insert the probes, the heat that began to generate was able to escape and cool the pile, then when the pile began to reheat, some of the sugars had already been consumed and so the heat generation did not peak as high as Pile 2 which had the probes inserted as it was built.

As seen in Figures 5, 6 & 13 both of the piles in this study retained heat throughout the trial period, with the Pile 1’s average temperature remaining above 40°C and Pile 2’s average temperature remaining above 50°C. When comparing the profiles it appears that Pile 1 and 2 produced heat at a similar rate. With Pile 2 warming slightly slower, but upon reaching approximately 62°C Pile 1 began to
lose heat for the rest of the trial. Pile 2 had a slightly slower rise in heat, and upon reaching its maximum heat, it did not lose its heat as rapidly. The overall average temperature of Pile 2, shows a rising temperature in mid-January; however, this appears to be a result of a failure in the probes, because the Top and Middle row of probes ceased functioning properly at this point, leaving only the data from the bottom row of probes, which were slowly gaining heat until the termination of the trial. Removing all data points after the middle and top probes ceased working shows the simulation is much more similar to the real-world data. The difference in heating for January is likely due to the probe malfunction, whereas the slower rate of heating and lower peak temperature may be a result of the pipe in Pile 2, which could have allowed better airflow through the pile and removing some of the heat.

It is also worth noting that there was no obvious direct correlation between ambient temperature and pile temperature. Figure 12 shows Pile 1 and 2’s temperature plotted against the 10-day average ambient temperature over the trial period. There is no clear pattern between the temperatures of the piles and the ambient temperature. This finding concurs with Bedane et al. (2011) who notes that larger piles are less affected by ambient weather conditions due to their own internal heating patterns.

Figure 12: Average pile temperatures compared to ambient temperature over the course of the trial
8.3.2 Comparison of Model Results with Trial Results

The model appears to be a good predictor of the overall temperature of Pile 2 (Figure 6), but it appears that the real-world data was affected by the heterogeneity of the self-heating in the pile. As seen in Figure 9, it appears that the middle and top portions of Pile 2 have the most similar shape to the model prediction simulations; however, the temperatures of the top layer of Pile 2 exceed the average with the middle portion of the pile remaining between 60 and 70°C, and the top portion exceeding 70°C, while the simulation is between 50 and 53°C. The reason the pile’s average temperature is far lower than actual temperature data, is due to the impact from the bottom portion of the pile, which heated up very slowly over the course of the whole trial, only reaching 60°C before the termination of the trial. The slow temperature decline in the pile is likely a result of the bark’s low thermal conductivity, causing the pile to retain much of its heat. Furthermore, the temperature differences for the pile sections are likely dependant on oxygen availability; Von Stockar & Birou (1989) noted that the heat generation of yeasts declined as oxygen became more limited and the yeasts were pushed to a fermentation metabolism. It is possible that oxygen is becoming limited into the lower portions of the pile, impeding heat production in the bottom, and slowing it in the middle. Oxygen consumption is accounted for in the Ferrero et al. (2009) model, however, modifications could be done to give a more accurate prediction of oxygen movement.

Figure 13: Average temperature profile of piles 1 and 2
As seen in Figures 8 & 9, Pile 1 was similar to Pile 2, with the top of the pile rising to 58°C by the end of November, with a peak at 61°C and then losing heat rapidly after mid-December and dropping to approximately 30°C by the termination of the trial. The middle of the pile rose to 69°C by mid-December and then, after rapidly dropping to 58°C by the end of December, it retained most of its heat throughout the trial, terminating at 47°C. The bottom of the pile tended to gain heat slowly, similar to Pile 2, with a rapid increase to 45°C by the end of December followed by a slow rise to 50°C by the termination of the trial. It is likely that the middle section’s insulated position meant that its low thermal conductivity allowed it to retain much of its heat. Meanwhile, the bottom portion’s slow heating, could be a result of oxygen limitations in the bottom of the pile preventing microbial respiration. The model did not fit Pile 1 as closely (Figure 5) as Pile 2; the model’s initial heating peaked 10°C below the real pile’s peak temperature, it did not heat as rapidly and by the end the model had not retained nearly as much heat as the trial. The model does not closely match the any section of the pile either. This is possibly related to a simplification in the model by the software. While, the porous nature of the bark results in a heterogeneous matrix, with a water fraction, a bark fraction and an air fraction; the Comsol software has to simplify these different fractions into one material for the pile, and in doing so it can simplify their unique thermal properties. Mitigation of this error was attempted by testing the material as a bulk substance, thus accounting for the different fractions. Furthermore, Ferrero et al. (2009) optimized the model for a smaller pile than the bark piles modeled in this trial; the pile in this trial is nearly 3 times longer than Ferrero et al. (2009), so there could be optimization issues for the model at larger pile sizes.

8.4 Sensitivity Analysis

An important component of testing this model was performing a sensitivity analysis in order to determine which variables were important for the temperature development of the model. Since the Ferrero et al. (2009) model is a theoretical framework of how a pile can heat, it is possible to individually change each parameter in the model in order to determine how they differ between bark and wood, and how they influence this difference in heating. Furthermore, the sensitivity analysis could inform future research aimed at reducing the risk of self-ignition of these piles by determining which parameters most affect self-heating. Table 8 displays a summary of the results from the sensitivity analyses performed on the model.
Table 8: Summary of results of sensitivity analysis for tested parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Description</th>
<th>Effect of Doubling Value on Temperature</th>
<th>Effect of Halving Value on Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB</td>
<td>Easily degradable fraction</td>
<td>Faster initial heating</td>
<td>Slower initial heating rate</td>
</tr>
<tr>
<td>Conversion to inert fraction</td>
<td>Conversion to inert fraction</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>Kh</td>
<td>Hydrolysis constant</td>
<td>Faster and Higher heating</td>
<td>Almost no heating</td>
</tr>
<tr>
<td>KMH</td>
<td>Substrate saturation constant for slowly degradable fraction</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>Kb</td>
<td>Substrate saturation constant for easily degradable fraction</td>
<td>No major change</td>
<td>No major change</td>
</tr>
<tr>
<td>Oxycaloric value</td>
<td>Heat generated per oxygen consumed by microbes</td>
<td>Increase</td>
<td>Decrease</td>
</tr>
<tr>
<td>Microbial growth rate</td>
<td>Microbial growth rate</td>
<td>No major change</td>
<td>Delayed but mostly similar heating</td>
</tr>
<tr>
<td>Microbial death rate</td>
<td>Microbial death rate</td>
<td>Almost no heating</td>
<td>Increased and faster heating</td>
</tr>
<tr>
<td>YCO2</td>
<td>Biomass yield on CO₂</td>
<td>No major change</td>
<td>No major change</td>
</tr>
<tr>
<td>Y</td>
<td>Biomass yield on MB</td>
<td>Faster heating</td>
<td>Decrease</td>
</tr>
<tr>
<td>Bulk Density</td>
<td>Bulk Density</td>
<td>No major change</td>
<td>Decrease</td>
</tr>
<tr>
<td>Convective heat flux</td>
<td>Convective heat flux</td>
<td>No major change</td>
<td>No major change</td>
</tr>
<tr>
<td>Height</td>
<td>Height</td>
<td>No major change</td>
<td>Decrease</td>
</tr>
<tr>
<td>Higher Heating Value</td>
<td>Higher Heating Value</td>
<td>No major change</td>
<td>No major change</td>
</tr>
<tr>
<td>Initial Oxygen Concentration</td>
<td>Initial Oxygen Concentration</td>
<td>No major change</td>
<td>No major change</td>
</tr>
<tr>
<td>Kinetic Factors</td>
<td>Activation Energy and Pre-Exponential Factor</td>
<td>No major change</td>
<td>N/A</td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>Specific Heat Capacity</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>Thermal Conductivity</td>
<td>Increase</td>
<td>Decrease</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>Moisture Content</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>O₂ Stoichiometric value</td>
<td>O₂ Stoichiometric value</td>
<td>No major change</td>
<td>No major change</td>
</tr>
<tr>
<td>Parameter</td>
<td>Parameter Description</td>
<td>Effect of Doubling Value on Temperature</td>
<td>Effect of Halving Value on Temperature</td>
</tr>
</tbody>
</table>
8.4.1 Biological Heating Source

The easily degradable fraction influences the initial temperature rise in the pile and while it does not necessarily increase the max temperature by a significant amount, by increasing the size of this fraction the initial heat-up of the pile is predicted to be more rapid than with a smaller easily degradable fraction (Figure 14). This can be explained by the preferential consumption of sugars in woody materials. Microbes will consume whatever sugars are available, which results in a higher rate of microbial activity (Fengel & Wegner, 1989; Springer & Hajny, 1970). Furthermore, as described in a review by Krigstin & Wetzel (2016), the living parenchyma will consume stored sugars remaining in the biomass and their respiration will produce heat. So, when less sugars are available there is a lower rate of microbial activity and the microbes must rely more on the conversion of slowly degradable matter to simple sugars before consumption. Additionally the living parenchyma cells can consume less sugar and generate less heat.

Another biological parameter that affects the temperature is the hydrolysis constant. This rate was important for estimating the rate of conversion of slowly-degradable material like celluloses and/or lignins to more easily degradable fractions. Doubling this parameter resulted in the initial heat increase in the pile to be much steeper, while halving resulted in the pile barely gaining any heat as most of the heat which was generated by the slow hydrolysis was dissipated. Similarly, the saturation constant for
the slowly-degradable fraction increased the temperature rise for the pile. This constant is an approximation of how concentrated a substrate is with slowly degradable matter for enzymatic processes to break down. Doubling this parameter resulted in an increase in peak temperature while halving it resulted in a drop in peak temperature; this is likely because enzymatic processes are dependent on nutrients and as more become available by increasing the substrate saturation constant, they are no longer limited by them (Owens & Legan, 1987).

Furthermore, the **biomass yield for each unit of easily degradable fraction consumed parameter** had a major effect on the temperature. The parameter dictates how many micro-organisms are produced by the consumption of each unit of easily degradable matter. Increasing this value had a similar effect to the hydrolysis rate, as the increase in the parameter resulted in more microbes being created from each unit of material consumed, and so they were able to break down the easily degradable fraction more quickly, resulting in steeper temperature rise when this value was doubled, but almost no temperature rise when this value was halved.

Another value that affected the temperature was the conversion of organic matter to inert. In the model from Tremier et al. (2005) from which the equations for the biological degradation were taken, they model a third fraction of the woody material called the “inert fraction”. This model does not monitor the inert fraction, but does take into account the conversion of material to inert through the use of a constant. The parameter is only found in the oxygen demand equation, and is used to predict the amount of oxygen required by the consumption of dead microbes by living ones. Halving the conversion value causes the heating rate to increase, while doubling the value causes the heating rate to decrease. This is likely because the microbes will require more oxygen to consume the dead material and so they increase the total oxygen demand of the model and because the biological temperature is based on oxygen demand, it increases the overall temperature generation.

The death rate, which is the amount of microbes dying per second, has a profound impact on the heating of the pile, and could be an adjustable parameter for future research. When the death rate is decreased, the heating rate rises more steeply and peaks higher before slowly dissipating. When the death rate is doubled, however, the heating of the pile is almost non-existent as the microbes cannot propagate enough to produce any significant heat (Figure 15). The last of the biological parameters to have an effect on the pile temperature was the oxycaloric value. This is the amount of energy released per unit of oxygen consumed by the microbes. Doubling the value caused the pile temperature to rise to a point where metabolism becomes limited. Halving the temperature causes it to rise, but it remains
lower than the normal oxycaloric value would be; this is simply because more energy is being produced per oxygen unit consumed in the pile.

![Graph showing sensitivity analysis of microbial death rate](image)

Figure 15: Sensitivity analysis of microbial death rate

8.4.2 Physical Parameters

In addition to the biological parameters, there are several physical variables that cause significant changes in the pile temperature when changed. Specific heat capacity is a physical parameter for the model that can significantly affect the temperature profile of the pile given that this parameter is the amount of energy required to raise the temperature of a material. When the specific heat capacity is increased it results in a lower overall temperature for the pile, whereas a lower heat capacity will cause the temperature to be higher, which is because more energy is required by the pile per unit of temperature increase. Likewise, when the parameter is decreased, less energy is required so the pile can increase in temperature much more rapidly.

The thermal conductivity is a parameter to indicate the ability of heat to move through a material. In this model, an increase in the thermal conductivity results in the pile cooling at a faster rate. When this parameter was decreased, as it should be for bark, it is becomes more difficult for heat to escape and so the pile will retain much more of the heat it generates. This is seen in Figure 16 with a decrease in the thermal conductivity showing now cooling after heating, while an increase in the parameter cooled far more rapidly.
As seen in Figure 17, bulk density can significantly affect the simulation temperature. This can occur for two reasons, the first is that in the model the fuel concentration is based on the bulk density. Alterations to the bulk density resulted in changes to the temperature profile, with an increase in the value adding increasing the temperature slightly, while a decrease resulted in a more pronounced decrease in temperature. These changes are likely a result of the increase or decrease in fuel density, resulting in a change in the amount of fuel for the microbes to consume. The differences in the results are likely because there is a limiting factor on the biological heating component, which prevents it from generating heat past roughly 60°C and so the temperature increase is more limited; it has been seen in real world examples that increasing the bulk density of a pile will increase its temperature (Jirjis, 1990). The bulk density parameter is also part of the heat transfer equation, which is used to estimate the transfer of heat through and out of the pile. When bulk density was increased there was more material for the heat to travel through, which resulted in more heat retention for the pile, and alternatively when the bulk density was decreased, the pile retained less heat.

Lastly, pile height has an effect on pile temperature. Doubling pile height does slightly increase the piles heat retention ability by adding more material for the heat to travel through, while halving the pile height results in the pile being unable to retain much heat and fluctuating its temperature with the weather (Figure 18). This has been observed in trials. Jirjis (2005) found that a 3 m pile of woodchips remained around ambient temperature for a month before heating up over the course of a month, while the 6 m woodchip piles heated up over the course of days and retained its heat for months. While
the 3 m chunkwood pile in this study did not gain any heat, aside from ambient weather, the 6 m pile was delayed by nearly 2 months before any major self-heating began, resulting in a peak temperature difference of nearly 60°C in some pile sections.

![Diagram](image)

**Figure 17: Sensitivity analysis of bulk density**

### 8.4.3 Parameters Which Caused No Effect

There were some parameters in the pile that had no effect on the temperature model. One such parameter is the substrate saturation constant for the easily degradable fraction, which is an approximation of how saturated the sugar fraction is with enzymes. When this parameter was increased or decreased there was no observable change in the temperature. When creating the microbial growth model used by Ferrero et al. (2009) in the self-heating model, Tremier et al. (2005) noted that the substrate saturation constant for the easily degradable fraction parameter had a low influence on the growth of the microbes. When the oxygen stoichiometric value was changed, so that more oxygen was produced from each reaction, there was no change in temperature for the pile. An increase or decrease in initial oxygen content did not change the temperature either, which could indicate that the pile is not oxygen-restricted (Figure 19). Given the values in Figures 8 & 9, it is likely that during the trial, the bottom sections of the pile were limited by oxygen due to their low self-heating. Therefore it may be an aspect of the model that should be refined and made more accurate for future studies.
The parameter for biomass yield per unit of CO$_2$ also resulted in no change in value, but this is not unexpected as the value does not affect the heat generation equation for the biological heat source, and so any alterations to the parameter should not affect temperature. Another parameter that did not change the heat was the convective heat transfer coefficient. This is a parameter for calculating the rate at which heat travels through a material by convection, it would be expected that when it was increased...
the pile would be unable to retain as much heat, but when this value was increased there was no change in the temperature profile.

Specific microbial growth rate for the pile did change the temperature when adjusted, but very minimally. The temperature profile for the value when it was doubled, was essentially the same as the normal growth rate value. When this value was halved, however, the heat generation of the pile was delayed by about 5 days, then it peaked at the same level as the normal value (Figure 20). It is likely that the microbial concentration becomes limited by the amount of degradable matter, so the increased growth rate does nothing to alleviate this.

![Figure 20: Sensitivity analysis of specific growth rate](image)

9. Recommendations

Given the opportunity to repeat or expand upon any aspects of this study, there are some recommendations which should be heeded. Firstly, additional trials involving internal temperature monitoring should have improved sensors, and real-time data uploading. While the type of probe was good up to 85°C, the probes could have ceased functioning due to the excessive heat in the piles, as probes in both piles registered temperatures as high as 85°C. This was not discovered until the end of the trial, because the data had to be collected from the physical probe. So, a probe that could resist higher temperatures and upload data wirelessly in real time would circumvent this issue. Real time monitoring would also be very useful to industry as they could react to overheating in the pile before it resulted in feedstock loss.
Furthermore, some changes and improvements to the Fabio et al. (2009) model could be carried out. Alterations to the mass transfer equation could be beneficial; one simple change could be creating a dynamic moisture to change the fraction of water in the pile as it is evaporated. Testing new moisture movement models could also improve the accessibility of the model, as the EV and CD coefficients are not wide-spread and could be replaced by easier-to-obtain parameters from other models. Incorporating an equation for estimating the bulk density from compaction at different levels within the pile could also improve the accuracy of the model. Further improvements could be made to bulk density and fuel density by incorporating the different components of the wood, such as lignin, cellulose, hemicellulose and extractives, as well as, different nutrients. Currently, the model assumes that every unit of fuel is homogenous, and does not take into account how the different woody components generate heat or how microbes would thrive on materials of different nutrient composition. Furthermore, the model does not incorporate any values for anaerobic respiration, as this can produce heat, as well. One of the assumptions for the model is that material properties are independent of time and temperature, improvements to the model could be made to eliminate this assumption, this could include regression formulae for heat sensitive parameters such as specific heat capacity, and microbial growth rate. Lastly, the heterogeneity of the pile self-heating was inaccurate compared to the findings of this study; additional methods should be considered to increase the accuracy of gas species movement throughout the pile.

There is much opportunity for new trials based on the findings of this research. It has been shown through simulation that the bark and wood-chip piles differed in their heat generation and it would be rewarding to set up a real-world trial, with a wood-chip pile and bark pile of similar size, shape, bulk density, and moisture content to observe how these simulated results play out in a real trial. Furthermore, this model worked well for the softwood bark piles studied, however, hardwood bark piles would likely behave very differently, such as degrading more slowly than a softwood possibly due to higher amounts of extractives. Allison & Murphy (1962) showed how hardwood bark degrades at a slower rate than sapwood, so a trial involving a primarily hardwood derived bark could yield different self-heating results.

Based on the sensitivity analysis, there are a variety of pile characteristics that could be altered in order to decrease the risk of self-heating. Increasing the pile microbe death rate through the use of a chemical application could decrease the total microbe quantity and lower the temperature output of this aspect of the pile. Decreasing the bulk density is also very helpful, whether by reducing compaction
or by increasing the particle size of the stored material, as a reduced bulk density will improve heat transfer out of the pile and reduce the available material for biological and chemical reactions. Finding a way to wash out the free sugars prior to storing material could also improve the self-heating by slowing the initial growth of the micro-organisms and slowing the plant cellular respiration when the pile is built. Micro-organisms would still decompose the wood, but the heat generation would be slower as the microbes would need to break down the slowly-degradable fraction in order to obtain sustenance. Lastly, decreasing the aeration of the pile could reduce self-heating; Jirjis (1995) found that a ventilated pile had higher proliferation of fungi, and Von Stockar & Birou (1989) reported that the heat generation of the fungi decreased as the oxygen became more restricted. This was a possible explanation for why the bottom portion of both piles self-heated so slowly, as they could have had a restricted flow of oxygen. So, replicating this restriction across the whole pile could reduce total self-heating by not allowing the microbes to aerobically respire.

10. Conclusions
   Based on the modeling of bark parameters obtained experimentally and wood parameters determined from a similar sized wood chip in Ferrero et al. (2009), it was determined that there are important physical and chemical parameters that differ between the bark and wood substrates which resulted in the model adapted to bark parameters matching the real-world trial at Port Hawkesbury much more closely. Thus when modeling the self-heating of a pile, the type of woody material must be taken into account or the accuracy of the model will suffer. Furthermore, it was determined that the use of the microbial parameters from Ferrero et al. (2009) fit the self-heating of the softwood bark modeled in this study due to the similarity of degradation between softwood bark and softwood whitewood.
11. References


Kelly, M. 2015. Personal Interview on November 12th.


Miles, Patrick D., and W. Brad Smith. 2009 Specific gravity and other properties of wood and bark for 156 tree species found in North America. *US Department of Agriculture, Forest Service, Northern Research Station. Research Note NRS-38*


