1649: Parameterisation of TLUD Cookstoves to Reduce Emissions

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Abstract

Over three billion people use biomass fuels such as wood, dung, and agricultural residues for cooking and heating requirements. The incomplete combustion of these fuels in traditional cookstoves results in harmful emissions - contributing directly to the deaths of four million people each year. Improved cookstoves that are capable of reducing harmful emissions have been developed. However, little rigorous scientific analysis has been undertaken in order to optimise their designs. The current project has helped to address this issue by undertaking a parametric analysis of a Top-Lit Up-Draft (TLUD) improved cookstove. The effect that several stove parameters had on stove performance was investigated. Analysing the effect that airflow rates had on stove performance revealed that secondary air fans will lead to greater improvements in stove performance than primary air fans. The location of fuel with a TLUD was also shown to be highly relevant, as well as the size of the fuel pieces combusted. The analysis culminated in the development of recommendations which it is hoped could assist in the design and development of optimised TLUD stoves.
Contents

Abstract i

Acknowledgements xvi

Signed Statement xvii

Acronyms xviii

1 Introduction 1

2 Literature Review 3

2.1 Current cookstove practices 4

2.1.1 Traditional cookstoves 4

2.1.2 Heating 5

2.1.3 Cultural customs 5

2.2 Fuels 6

2.2.1 Wood 8

2.2.2 Agricultural residues 8

2.2.3 Animal dung 9

2.2.4 Briquettes 10

2.3 Combustion of biomass fuels 11

2.3.1 Temperature and the combustion process 11

2.3.2 Rate of combustion 12
4.2 Testing stove modifications .............................................. 43
  4.2.1 Primary air set-up .................................................. 44
  4.2.2 Secondary air set-up .............................................. 45
  4.2.3 Summary of modifications ........................................ 50
4.3 Data collection .......................................................... 50

5 Commissioning ........................................................... 52
  5.1 Fuel selection .......................................................... 52
  5.2 Stove configuration and procedures ............................... 53
  5.3 Data collection .......................................................... 55
  5.4 Testing stove operation ............................................... 55
    5.4.1 Expected TLUD stove operating characteristics ............ 56
    5.4.2 Photographic evidence .......................................... 57
    5.4.3 Emissions data .................................................. 57
    5.4.4 Temperature data ............................................... 59
    5.4.5 Summary .......................................................... 60

6 Benchmarking ............................................................ 61
  6.1 Stove configuration .................................................. 61
  6.2 Fuel selection .......................................................... 62
    6.2.1 Type of bark chips .............................................. 63
    6.2.2 Moisture content ............................................... 63
    6.2.3 Mass of fuel ..................................................... 65
  6.3 Benchmark testing ................................................... 66
    6.3.1 Emissions .......................................................... 66
    6.3.2 Stove temperatures ............................................. 71
  6.4 Summary ............................................................... 74

7 Effect of Primary Airflow ............................................... 75
  7.1 Stove configuration .................................................. 76
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2</td>
<td>Methodology</td>
<td>76</td>
</tr>
<tr>
<td>7.2.1</td>
<td>Limitations</td>
<td>77</td>
</tr>
<tr>
<td>7.3</td>
<td>Primary airflow rate bounds</td>
<td>78</td>
</tr>
<tr>
<td>7.4</td>
<td>Results</td>
<td>79</td>
</tr>
<tr>
<td>7.4.1</td>
<td>Error analysis</td>
<td>80</td>
</tr>
<tr>
<td>7.4.2</td>
<td>Emissions</td>
<td>81</td>
</tr>
<tr>
<td>7.4.3</td>
<td>Temperature</td>
<td>86</td>
</tr>
<tr>
<td>7.4.4</td>
<td>Water boiling tests</td>
<td>87</td>
</tr>
<tr>
<td>7.5</td>
<td>Temperature control</td>
<td>89</td>
</tr>
<tr>
<td>7.6</td>
<td>Summary</td>
<td>89</td>
</tr>
<tr>
<td>8</td>
<td>Effect of Secondary Airflow</td>
<td>92</td>
</tr>
<tr>
<td>8.1</td>
<td>Stove configuration</td>
<td>92</td>
</tr>
<tr>
<td>8.2</td>
<td>Methodology</td>
<td>93</td>
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<td>93</td>
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<td>8.5.3</td>
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<td>101</td>
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<td>Effect of Fuel Size</td>
<td>102</td>
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<td>9.1</td>
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<td>Emissions results</td>
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<tr>
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<td>Temperature</td>
<td>105</td>
</tr>
<tr>
<td>9.3.4</td>
<td>Water boiling tests</td>
<td>108</td>
</tr>
</tbody>
</table>
A.1 Testing stove dimensions ........................................ 150
  A.1.1 Primary air set-up ........................................ 151
A.2 Secondary air set-up ........................................... 153
  A.2.1 Chimney used for natural secondary air testing ......... 154
  A.2.2 Chimney used for controlled secondary air testing .... 157
A.3 Measurement apparatus ....................................... 159
  A.3.1 Gas analyser .............................................. 159
  A.3.2 Thermocouples ........................................... 160
  A.3.3 Flow meters and floats ................................. 160

B Commissioning & Preliminary Testing .......................... 164
  B.1 Stove configuration ........................................ 164
  B.2 Testing procedures ........................................ 166

C Fuel Preparation ............................................... 168
  C.1 Bark chip preparation procedure ........................... 168
  C.2 Dung preparation procedure ............................... 170
  C.3 Moisture content determination ............................ 173
    C.3.1 Moisture content determination equation ............. 173

D Natural Draft Testing .......................................... 174
  D.1 Stove configuration ........................................ 174
  D.2 Testing procedures ........................................ 176

E Controlled Primary Air Testing ................................ 178
  E.1 Stove configuration ........................................ 178
  E.2 Testing procedures ........................................ 180

F Controlled Secondary Air Testing ............................. 183
  F.1 Stove configuration ........................................ 183
  F.2 Testing procedures ........................................ 185
List of Tables

2.1 Global and regional biofuel consumption estimates in 2000 (Fernandes et al., 2007) ........................................ 7
2.2 Benefits of cleaner cooking (Rehfuss, 2006) .......................... 16
6.2 Normalized benchmarking data ........................................ 72
7.1 Effect of primary air - key findings ................................... 91
8.1 Effect of secondary air - key findings ................................ 101
9.1 Effect of fuel size - key findings ..................................... 111
10.1 Effect of fuel stack location - key findings ......................... 118
A.1 Flow meters and floats .................................................. 163
L.1 Benchmarking normalized data for all combustion phases ......... 210
L.2 Benchmarking non-normalized data for all combustion phases ... 211
L.3 Primary air data for initial combustion phase ....................... 212
L.4 Primary air data for steady-state combustion phase ................ 213
L.5 Primary air normalized data for final combustion phase .......... 214
L.6 Primary air non-normalized data for final combustion phase ...... 215
L.7 Secondary air data for initial combustion phase .................... 216
L.8 Secondary air data for steady-state combustion phase ............. 217
L.9 Secondary air normalized data for final combustion phase ......... 218
L.10 Secondary air non-normalized data for final combustion phase . . . . 219
L.11 Varying fuel size data for initial combustion phase . . . . . . . . . 220
L.12 Varying fuel size data for steady-state combustion phase . . . . . 221
L.13 Varying fuel size normalized data for final combustion phase . . . 222
L.14 Varying fuel size non-normalized data for final combustion phase . . 223
L.15 Separation distance data for initial combustion phase . . . . . . . . 224
L.16 Separation distance data for steady-state combustion phase . . . . 225
L.17 Separation distance normalized data for final combustion phase . . 226
L.18 Separation distance non-normalized data for final combustion phase . 227
L.19 Temperature data for primary air and secondary air . . . . . . . . . 228
L.20 Temperature data for fuel size and separation distance . . . . . . . 229
L.21 Water boiling test data for primary air and secondary air . . . . . . 230
L.22 Water boiling test data for fuel size and benchmarking . . . . . . . 231
List of Figures

2.1 Traditional cooking technologies (Wordpress, 2014) ................. 5
2.2 Distance travelled to collect fuelwood (Tanzanian National Bureau of Statistics, 2001) ................................................................. 9
2.3 Rocket stove (The Survival Center, 2014) .............................. 20
2.4 TLUD stove ................................................................. 21
2.5 Vivek stove (Bhanap & Deshmukh, 2012) .............................. 25
2.6 Testing TLUD stove schematic ........................................... 27
2.7 Berkeley-Darfur cookstove (TEL, 2014) .............................. 29

3.1 Schematic diagram cross-section showing the restrictor disk location . 36

4.1 Testing stove schematic diagram ........................................... 41
4.2 Testing stove with primary air chamber panels removed and no chimney 42
4.3 The actual fuel grate used, and a schematic showing its location within the stove ............................................................... 43
4.4 The inherited fan that was previously used for forced primary air . 44
4.5 Compressed air fitting for primary air inlet .......................... 45
4.6 Primary air diffuser ....................................................... 46
4.7 The chimney that was used for all natural buoyancy tests ........ 47
4.8 Combustion at secondary air inlet ....................................... 47
4.9 The chimney that was used for all forced secondary air tests . . 48
4.10 A schematic diagram showing the basic dimensions of the secondary air diffuser .......................................................... 49
4.11 Wool hanging in the chimney shows the difference in the swirl between 0 and 574 L/min .......................................................... 49
4.12 A diagram showing the data collection set-up ...................... 51

5.1 Stove configuration used for commissioning ......................... 54
5.2 Combustion of volatile gases evolved from pre-heated fuel ........ 58
5.3 CO emission profiles from commissioning testing .................. 59
5.4 Temperature profiles from commissioning testing .................. 60

6.1 The three type of bark chips evaluated ................................ 62
6.2 Temperature of pre-combusted volatiles within the stove for different bark chips ......................................................... 64
6.3 Temperature of pre-combusted volatile gases for dried and un-dried Tatura pine bark chips .................................................. 65
6.4 Benchmarking emissions traces .......................................... 70
6.5 Determining times of combustion phase transition ............... 73
6.6 Demonstration of identifying combustion phases using a normalized CO emissions profile ................................................. 73
6.7 Mean temperatures of volatile gases pre and post combustion . 74

7.1 Minimum steady-state temperature of pre-combusted volatile gases for varying primary airflow rates ......................... 79
7.2 Mean normalized CO emissions in steady-state for varying primary airflow rates ......................................................... 80
7.3 Mean normalized peak CO in initial phase for varying primary airflow rates ................................................................. 81
7.4 Mean time in initial phase for varying primary airflow rates ...... 82
7.5 Mean normalized CO\textsubscript{2} emissions in steady-state for varying primary airflow rates ........................................... 83
7.6 Mean normalized NO\textsubscript{x} emissions in steady-state for varying primary airflow rates ........................................... 84
7.7 Mean time in steady-state phase for varying primary airflow rates .... 84
7.8 Mean normalized CO emissions in the final phase for varying primary airflow rates ........................................... 85
7.9 Mean normalized CO peak in final phase for varying primary airflow rates ........................................... 86
7.10 Maximum temperature within chimney for varying primary airflow rates ........................................... 87
7.11 Maximum water temperature for varying primary airflow rates ....... 88
7.12 Average heating rate of water for varying primary airflow rates ....... 88
7.13 Heat transfer to water and pot for varying primary airflow rates ....... 89
8.1 Mean normalized CO in steady-state phase for varying secondary airflow rates ........................................... 94
8.2 Mean normalized CO and H\textsubscript{2} peaks in initial phase for varying secondary airflow rates ........................................... 97
8.3 Mean normalized CO in final phase for varying secondary airflow rates ........................................... 98
8.4 Mean normalized NO\textsubscript{X} in final phase for varying secondary airflow rates ........................................... 98
8.5 Maximum temperature within chimney for varying secondary airflow rates ........................................... 99
8.6 Heat transfer to water and pot for varying secondary airflow rates .... 100
8.7 Average heating rate of water for varying secondary airflow rates .... 100
9.1 Normalized CO emissions traces for varying SAVRs ................. 106
9.2 Mean normalized CO emissions in steady-state phase for varying SAVRs107
9.3 Mean minimum temperature of pre-combusted volatiles in the steady-state phase for varying SAVRs .................................. 107
9.4 Maximum water temperature for varying SAVRs .................................. 108
9.5 Average heating rate of water for varying SAVRs .................................. 109
9.6 Heat transfer to water and pot for varying SAVRs .................................. 109

10.1 Normalized CO emissions traces for varying separation distances . . . 115
10.2 Mean normalized CO emissions in steady-state phase for varying separation distances .................................. 115
10.3 Mean normalized peak CO in initial phase for varying separation distances .................................. 116
10.4 Mean time in steady-state phase for varying separation distances . . . 116
10.5 Maximum temperature within chimney for varying separation distances 117

11.1 Normalized CO traces for varying fuel stack depths ......................... 121

II.1 Meeting with Tim Costello, CEO of World Vision Australia ............... 148
II.2 Channel TEN program - Scope filming ........................................ 148

A.1 Basic dimensions of testing stove ................................................ 150
A.2 Measurement locations .............................................................. 151
A.3 Compressed air fitting for primary air inlet ..................................... 152
A.4 Basic Dimensions of chimney used for natural draft testing ............... 155
A.5 The base of the natural draft chimney, showing the slits cut to allow the chimney to fit inside the stove. ................................. 156
A.6 Basic dimensions of chimney used for forced air testing .................... 158
A.7 Testo probe location within extractor hood directly above cookstove . 161
A.8 The available thermocouple locations .......................................... 162

B.1 Stove configuration used to commission stove ............................... 165

C.1 Bark chips on trays ................................................................. 169
C.2 Enclosure for bark chip moisture control ............... 169
C.3 Dung preparation equipment ........................................ 172
D.1 Stove configuration used for natural draft testing ......... 175
E.1 Stove configuration used for primary air testing .......... 179
F.1 Stove configuration used for controlled secondary air testing ....... 184
G.1 Stove configuration used for fuel stack location testing .... 189
H.1 Stove configuration used for shaped fuel testing .......... 194
I.1 Stove configuration used for fuel stack depth testing ...... 200
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**Signed Statement**

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of our knowledge, contains no material previously published or written by another person, except where due reference has been made in the text.

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SIGNED: ..................... DATE: .....................
Acronyms

CO    Carbon monoxide
CO$_2$  Carbon dioxide
GACC  Global Alliance for Clean Cookstoves
H$_2$  Hydrogen
IAP   Indoor air pollution
IDP   Internally displaced persons
IEA   International Energy Agency
NO$_X$  Nitrogen oxides
SAVR  Surface area to volume ratio
TLUD  Top-lit up-draft
TWA   Time weighted average
WBT   Water boiling test
WHO   World Health Organisation
UN    United Nations
Chapter 1

Introduction

Currently 40% of the world’s population relies on biomass fuels such as wood, agricultural residues, and animal dung for cooking and heating purposes (Hutton et al., 2007; Smith et al., 1993). These fuels are often combusted inefficiently in traditional cookstoves, leading to the evolution of high concentrations of harmful emissions known as Indoor Air Pollution (IAP). Exposure to these emissions results in the deaths of approximately four million people annually (Lim et al., 2013). In an effort to address this problem improved cookstoves which aim to reduce harmful emissions, fuel consumption, and cooking times have been developed.

Semi-gasifier cookstoves have been promoted as a next-generation improved cookstove technology (Kshirsagar & Kalamkar, 2014). One such semi-gasifier stove is the Top-Lit Up-Draft (TLUD) stove. Several types of TLUD stoves are on the market today, and they have been disseminated in developing countries with the intent of reducing IAP. Despite the prevalence of TLUD stoves, relatively little rigorous scientific analysis has been undertaken to optimise their design. The current project has made progress to address this issue by undertaking a parametric analysis of a TLUD stove. This analysis was accomplished by using a purpose built testing stove
which enabled the independent control of several stove parameters, which were: the primary airflow rate, the secondary airflow rate, the fuel stack location, and the fuel size. Following analysis of the data for each parameter, recommendations regarding TLUD stove design and operation were made.

The following report begins with a literature review investigating cooking technologies used in the developing world, as well as types of improved cookstoves currently in use. Chapter three outlines the scope and goals of the current project. Chapter four discusses the equipment used, and Chapter five investigates the suitability of the apparatus by subjecting it to a formal commissioning process. Chapters six through eleven analyse the testing stove’s operation for different parameter configurations. Recommendations to assist in the design of TLUD stoves are made in Chapter twelve. Recommendations regarding future work are presented in Chapter 13, with Chapter 14 setting out conclusions.
Chapter 2

Literature Review

Over three billion people rely on biomass fuels such as wood, dung, and agricultural residues - approximately 10% of total world energy usage (Hutton et al., 2007; Granderson, 2009). When these solid fuels are combusted in traditional stoves the emissions produced can have severe health consequences. Lim et al. (2013) estimate that between 2.6 and 4.4 million people die each year as a result of exposure to indoor air pollution. In an effort to address this global health problem improved cookstoves have been developed. These stoves aim to reduce harmful emissions, fuel use, and cooking time.

The following literature review will first examine traditional cooking methods and fuels used in the developing world. The combustion science underpinning the operation of traditional stoves will then be examined. In particular the products of combustion from biomass burning cookstoves will be discussed, and the potential health impacts of these emissions on stove users analysed. The magnitude of these health impacts will then be demonstrated. The review will then explore the health, economic, social, and environmental benefits associated with improved cookstove use, and will conclude with an overview of the current state of improved cookstove research.
2.1 Current cookstove practices

A variety of cookstove technologies are currently utilised in the developing world. Typically, these stoves are cheap, easily constructed, and versatile. However these simple stoves often have many disadvantages. These include: poor combustion efficiencies, large fuel requirements, and negative health impacts. The use of such stoves is not limited to meal preparation alone, as they can also service heating requirements within the household.

The role stoves play in the cultural context of a community should also be considered, as more efficient cooking technologies may not necessarily be accepted by traditional stove users. Cultural norms may significantly impact adopting new more efficient stoves.

2.1.1 Traditional cookstoves

The most common type of stove used is the three-stone fire. The three-stone fire is inexpensive and simply constructed. Figure 2.1a shows the operation of a three-stone fire. It is created by positioning three stones such that a pot may be placed on top of them. A fire burns in the centre of the three stones beneath the pot. The stones not only provide a place on which a pot can be placed, but also helps shield the fire from wind. This concept of shielding has been further developed in traditional mud cookstoves shown in Figure 2.1b. These stoves are constructed in a U-shape, with the side walls protecting the centrally located fire from the elements. An opening at the front of the stove allows fuel to be fed in, and entrainment of air to facilitate more complete combustion (Sharma, 1993). The fuels used can be wood, dung, and agricultural residues. The versatility of fuel usage, in conjunction with its simple design, is conducive to its uptake in poor rural communities. However the three-stone cookstove has many shortcomings. These include: rather large fuel
CHAPTER 2. LITERATURE REVIEW

2.1.2 Heating

Traditional cookstoves can be used for heating as well as cooking purposes. Typically the three-stone fire and traditional mud cookstoves combust biomass inefficiently, which results in hazardous emissions. Compounding this problem, these stoves are often used in poorly ventilated dwellings. Prolonged exposure to these emissions can have a negative health impact on users (Kumar et al., 2013).

2.1.3 Cultural customs

Cultural customs can have a significant effect on the uptake of new cooking technologies. Those within communities with access to electricity may still choose to cook with wood or biomass. For instance, in recent years Bhutan has increased the accessibility of electricity to rural areas. Approximately 70% of Bhutan’s population lives in rural areas. Bhutan has an abundance of wood fuel, with forests...
accounting for 70% of the country’s landmass. It was expected that as electricity, and consequently electric cooking technologies became more available, the demand for woodfuel would decrease. However this has not been the case. While electric rice cookers have been widely accepted, traditional cooking methods are preferred for certain dishes, such as curries (Bruce et al., 2013). Therefore cultural norms can have a pervasive influence on the uptake of new cooking technologies.

2.2 Fuels

The dependence on biomass as a fuel is particularly high in less developed countries. It is estimated that biomass accounts for approximately 38% of primary energy consumption in developing countries, and that in rural areas this figure can exceed 90% (Bhattacharya & Abdul Salam, 2002). The literature suggest that this dependence is related to income (Heltberg, 2005; Lewis & Pattanayak, 2012; Viswanathan & Kumar, 2005). Households with higher incomes tend to burn cleaner fuels (such as LPG or biogas) than poorer households who predominantly rely on biomass.

Factors that can influence the type of fuel combusted in developing countries are: climate, terrain, and social customs (Yevich & Logan, 2003; Leach, 1988; Meyers & Leach, 1989). Despite the regional variability associated with these determinants, there are four types of biomass which are predominantly combusted in developing countries. These are agricultural residues, wood, charcoal, and dung. Table 2.1 summarises the proportions in which these fuels are used in different geographic regions.

Table 2.1 illustrates the heavy reliance on wood fuels throughout the developing world. At a global level, wood fuel accounts for more than half of total biomass combusted in developing countries. Africa in particular relies heavily on wood fuel, where wood fuel constitutes approximately 75% of the total biomass combusted.
### Table 2.1: Global and regional biofuel consumption estimates in 2000 (Fernandes et al., 2007)

<table>
<thead>
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<th>World Region</th>
<th>Fuelwood</th>
<th>Crop Residues</th>
<th>Dung</th>
<th>Charcoal</th>
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<td>75</td>
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*Units are million t/year*
Agricultural residues are combusted intensively in Asia. Dung is less commonly combusted than both agricultural residues and wood fuel in all the geographic regions. However, dung can be used intensively in areas which are devoid of other fuel alternatives. For instance, in India’s largest state, Uttar Pradesh, dung accounts for 63% of the total biomass combusted (Yevich & Logan, 2003).

2.2.1 Wood

Wood is the most popular fuel source used in developing countries, and it is estimated that over 90% of some rural populations use fuelwood for cooking (Fernandes et al., 2007; Kim Oanh & Dung, 1999). Inefficient traditional stoves that combust wood incompletely, lead to the formation of harmful emissions (Zhang et al., 1999). Despite the potential health effects, the low cost and relative availability of wood often makes it the only viable option for many households.

Individuals can be required to travel long distances in search of fuelwood. In Tanzania the average distance travelled by residents in different regions to collect fuelwood is shown in Figure 2.2. Residents collecting fuelwood in rural areas may be required to travel distances in excess of 10km. Such distances are also observed in the vicinity of several displaced persons camps in Chad and Sudan (Galitsky et al., 2006; Comission, 2014).

2.2.2 Agricultural residues

Agricultural residues are the by-products of agricultural production (such as husks and stalks). Crops associated with the most commonly burned residues are: wheat, rice, barley, maize, millet, and sorghum (Yevich & Logan, 2003). Carbon is sequestered into these residues seasonally, and if managed appropriately can be con-
considered a sustainable fuel resource. However, the combustion of this type of biomass can have severe health and environmental consequences. Uncompacted residues combust incompletely in traditional stoves, leading to the evolution of hazardous emissions (Bhattacharya & Abdul Salam, 2002).

### 2.2.3 Animal dung

In areas where fuelwood is scarce, animal dung is often combusted as a substitute. Undigested botanical matter constitutes a large proportion of dung (Anderson & Ertug-Yaras, 1996). There are numerous methods for preparing dung for combustion, and a standardised preparation procedure does not exist in the developing world. Despite the many potential variations, a general preparation procedure typically involves moulding dung into circular disks and then sticking these disks onto
walls and roofs to dry (Care for Cows International, 2014). It should be noted that in addition to being a viable fuel source, dung can also be used as a fertiliser. Therefore the opportunity cost of combusting dung is high when compared to other fuels. This suggests that dung is often combusted out of necessity rather than preference (Bhattacharya & Abdul Salam, 2002).

2.2.4 Briquettes

Agricultural residues such as husks and stalks have low densities, necessitating the transport of large volumes in order to service even modest energy requirements (RWEDP, 2014). This is often uneconomic. Increasing the density of loose biomass fuels helps address this issue. One such process is called briquetting. The process involves creating a pulp that is then compressed into a particular shape. Briquettes can be made with biomass exclusively, or they can incorporate other composite materials such as coal (Yamada et al., 2008).

Briquetting is shown to enhance the combustion characteristics of some fuels (Chaney, 2010; Nasrin et al., 2008; Laichenha, 1993). Significant reductions in hazardous emissions have been observed with the combustion of briquetted coal (Zhi et al., 2009; Yamada et al., 2008). This reduction in harmful emissions is thought to be a result of an increase in density. Increasing the density of a fuel impedes the motion of volatiles heated near the surface of the fuel. This increases the residence time of the volatiles within the solid fuel, thereby increasing the chance of secondary reactions occurring (Zaror & Pyle, 1982). These secondary reactions decompose the volatiles into less harmful emissions. Therefore densification has the potential to reduce the quantity of volatile emissions evolved.
2.3 Combustion of biomass fuels

Several stages are associated with the combustion of solid biomass fuels. When a biomass fuel increases in temperature sufficiently, the fuel breaks down and releases volatile gases in a process known as pyrolysis (Demirbas, 2004). The temperature of the biomass fuel will dictate the stage of the combustion process, and the rate of release of volatiles from the fuel. These volatile gases then mix with oxygen and combust.

Different types of biomass have varying combustion characteristics. This literature review will focus on the combustion process associated with wood, as wood is the most commonly combusted type of biomass in the developing world (Fernandes et al., 2007). Analysing the combustion characteristics of wood will give an insight into the operation of a large proportion of the hundreds of millions of biomass stoves used throughout the world.

2.3.1 Temperature and the combustion process

The effect that temperature has on the combustion of woodfuel is first examined. When wood is heated to 100 °C water in the wood grain migrates to cooler parts of the grain and then evaporates. At 200 °C the hemi-cellulose begins to decompose, followed by the cellulose at 300 °C. This process releases decomposed organic hydrocarbons, leaving around 8-15% cellulose and hemicellulose, and approximately 50% of lignin as char, otherwise known as bio-char or fixed carbon. Volatiles escape the wood at a temperature of approximately 1100 °C. The gaseous volatiles then mix with air and are then cooled to approximately 550 °C where they burn (Kumar et al., 2013).

The exhaustion of volatile matter from a biomass fuel will eventually result in the
cessation of a flame. In these final stages of combustion, the fuel will continue to undergo pyrolysis until its temperature drops sufficiently. The top layer of char that remains is now porous and slows down escaping volatiles from lower layers. This in turn catalyses the breakdown of the volatiles into smaller, lighter and more reactive gases, resulting in more complete combustion. Near the surface of this upper char layer carbon dioxide at approximately 800 °C can react with carbon to form carbon monoxide. Carbon monoxide is either combusted if mixed with oxygen at a sufficiently high temperature, or is emitted from the stove into the atmosphere (Kumar et al., 2013).

2.3.2 Rate of combustion

The rate of combustion is controlled by the rate of release of volatiles from a fuel. The combustion of volatiles results in radiant heat which in turn heats the fuel. This mechanism helps to sustain the temperature of the fuel, and in turn the rate of release of volatiles. As the fuel supply is exhausted, the rate of release of volatiles decreases which slows the rate of combustion, eventually causing the flame to extinguish (Kumar et al., 2013).

2.3.3 Fuel size

Fuel size can also affect the combustion process. Yang et al. (2005) find that as the size of woodfuel decreases, the rate of combustion increases. An increase in the surface area of a fuel allows water to evaporate more readily, allowing faster ignition. As the surface area increases, so do the number of potential sites from which volatile gases may escape, thereby increasing the rate of release of volatiles.
2.4 Emissions

The burning of biomass produces a variety of emissions, predominantly carbon monoxide (CO), unburned hydrocarbons, and particulate matter (PM) (Smith, Samet, Romieu & Bruce, 2000). These emissions result from the incomplete combustion of biomass. Emissions in relatively lower concentrations such as nitrogen oxides (NO\textsubscript{X}) and sulphur oxides (SO\textsubscript{X}) are also observed to form when solid biomass is combusted (Raiyani et al., 1993).

The composition of different biomass fuels can influence the emissions evolved. Biomass fuels emit higher concentrations of carbon monoxide, nitrogen dioxide, sulphur dioxide, and formaldehyde than kerosene and liquefied petroleum gas (Raiyani et al., 1993; Kandpal et al., 1994\textsuperscript{b}). The concentration of these emissions is found to be highest directly above the stove, at the standing height of the user (Kandpal et al., 1994\textsuperscript{a}).

Even relatively small quantities of some elements in biomass can lead to significant hazardous emissions if combusted. For instance, sulphur typically constitutes less than 1% of the dry weight of biomass, yet can have a considerable impact on the volatile emissions evolved. The sulphur content of a fuel can lead to the formation of sulphur oxides during combustion (Jenkins et al., 1998). Sulphur dioxide when mixed with water in the atmosphere reacts to form sulphuric acid, which can result in acid rain. There are also potential health consequences for humans. Exposure to sulphur dioxide can cause irritation to the respiratory system, in particular among those suffering from asthma (Balmes et al., 1987).

High flame temperatures can cause nitrogen and oxygen in air to react to form nitrogen oxides (NO\textsubscript{X}). Nitrogen oxides have negative environmental and health consequences. Kagawa (1985) shows that prolonged exposure to nitrogen oxides can result in lung problems in humans. Nitrogen dioxide also has negative environmental
consequences. When combined with water in the atmosphere it can form nitric acid, resulting in acid rain. NO\textsubscript{X} is also ozone depleting, and in the presence of sunlight can form photochemical smog (EPA, 2014).

2.5 Health impacts

The inhalation of hazardous emissions evolved from biomass burning cookstoves can significantly affect the health of users. Inhaling indoor air pollutants can lead to increased incidence of lower respiratory infections, chronic obstructive pulmonary disorder, increased blood pressure, cataracts, low birth weight, and increased susceptibility to tuberculosis and lung cancer (McCracken et al., 2007; Naeher et al., 2007; Pokhrel et al., 2005; Pope et al., 2010; Bruce et al., 2000). As mothers and children often spend long periods indoors, they are more susceptible to ill health. There is also strong evidence suggesting a causal relationship exists between long-term exposure to IAP and acute respiratory infections in children (World Bank, 2010). The extent of this health problem is significant, with IAP being responsible for between 3-5% of the global burden of disease, and up to 4.4 million deaths per year (Lopez et al., 2006; Smith & Mehta, 2003; Lim et al., 2013).

2.6 Improved cookstoves

Improved cookstoves involve technologies which attempt to address the problem of IAP by combusting solid fuels more efficiently. In doing so these stoves improve the usable energy output of the fuel consumed, remove smoke from the cooking environment, and lessen the difficulties associated with cooking. Further, improved cookstoves generally outperform traditional cookstoves (Bryden et al., 2002).
CHAPTER 2. LITERATURE REVIEW

The combustion efficiency of a stove can be defined as the ratio of the useful energy extracted relative to a fuel’s total potential energy. Improved cookstoves have been shown to achieve combustion efficiencies between 15-35%; in contrast traditional cookstoves typically only achieve efficiencies of between 10-14% (Ravindranath & Balachandra, 2009). An increase in combustion efficiency reduces the fuel requirement for cooking, and provides indirect benefits, such as a reduction in the time spent gathering fuel (US Department of Energy, 2011).

India during the 1940s saw significant development of biomass burning cookstoves (Anhalt & Holanda, 2009). The 1970s oil crisis spurred renewed efforts to improve cookstove designs. This led to the formation of many research and development programs, which focused on reducing IAP within households and environmental impacts (such as deforestation). The semi-gasifier cookstove was developed during this period, which operates by partially combusting a solid fuel, forming a volatile gas mixture. The gaseous volatiles are then mixed with air and are combusted. The semi-gasification of the fuel results in better mixing between air and fuel, and more complete combustion. When compared to a traditional three-stone fire, semi-gasifier cookstoves can reduce particulate matter by up to 90% (MacCarty et al., 2010).

2.6.1 Benefits of improved cookstoves

Improved cookstoves have many benefits associated with their use. A reduction in hazardous emissions can lead to better health outcomes for users. In addition, higher combustion efficiencies relative to traditional cookstoves can lower a household’s fuel requirement. Consequently improved cookstoves bring about positive environmental, economic, and social benefits in the communities in which they are used (Edwards et al., 2003; Ballard-Tremeer & Jawurek, 1996; McCracken & Smith, 1998).
### Benefits of Cleaner Cooking

<table>
<thead>
<tr>
<th>Benefits of Cleaner Cooking</th>
<th>Benefit (USD bn per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health-care savings</td>
<td>0.38</td>
</tr>
<tr>
<td>Time savings due to childhood and adult illnesses: school attendance days gained for children and productivity gains for children and adults</td>
<td>1.46</td>
</tr>
<tr>
<td>Time savings due to less time spent on fuel collection and cooking: productivity gains</td>
<td>43.98</td>
</tr>
<tr>
<td>Value of deaths averted among children and adults</td>
<td>38.73</td>
</tr>
<tr>
<td>Environmental benefits</td>
<td>6.07</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>90.62</strong></td>
</tr>
</tbody>
</table>

Table 2.2: Benefits of cleaner cooking (Rehfuess, 2006)

### Economic benefits

The economic benefits of improved cookstoves typically include: time and cost savings due to lower fuel consumption, health benefits from cleaner burning stoves, and time savings associated with shorter cooking times (Malla et al., 2011). Table 2.2 shows the estimated benefits associated with cleaner cooking technologies.

The data in Table 2.2 shows the societal benefits arising from the dissemination of LPG stoves in eleven WHO subregions. These savings are forecast by taking 2005 as the base year, and allowing a ten year time horizon over which LPG stoves are provided to half the population of biomass stove users. Productivity gains are associated with less time spent collecting fuel. Adverse health effects averted
constitute the largest benefits realised. The latter benefit is calculated by estimating the potential output to society lost as result of illness or premature death. These gains are significant when compared to the cost of stove dissemination. In 2006 it was estimated that providing LPG stoves to half the population of traditional biomass stove users would cost at most USD 1.5bn per year until 2015 (IEA, 2006). This would result in a benefit-to-cost ratio (in 2015) of approximately 6.7 to 1 (assuming the USD 90.62bn benefit is only realized in 2015). This is consistent with other benefit-to-cost ratios estimated in the literature. Hutton et al. (2007) estimate that the global economic benefits from improved cookstoves outweigh the costs by a ratio of seven to one. Other case studies have reported higher ratios. Malla et al. (2011) find that the benefit-to-cost ratio of cookstove investment in Kenya was 21 to 1. These ratios support the economic argument for increased dissemination of improved cookstoves in developing countries.

**Health benefits**

The inhalation of smoke from cookstoves has the potential to cause severe illnesses. Illnesses, such as lower respiratory infections account for the greatest proportion of child deaths in the developing world. The risk of a child developing such an infection is increased with increased exposure to IAP (Smith, Samet, Romieu & Bruce, 2000). The illness not only impacts the person afflicted, but often other members of the family who must act as carers (Malla et al., 2011), which decreases their capacity to work and generate income. A lower income often forces households to adopt the use of lower quality fuels which result in the evolution of higher concentrations of harmful emissions (Kavi Kumar & Viswanathan, 2007). Improved cookstoves have the capacity to break this negative cycle, lift health outcomes, increase productivity, and economic benefits.
Environmental benefits

The use of biomass fuels for cooking brings with it several environmental challenges. MacCarty et al. (2008) show that improved cookstoves have a lower global warming impact than traditional cookstoves. In particular, they find that when biomass is harvested sustainably, improved cookstoves can reduce the global warming impact associated with products of incomplete combustion by between 50-95%. Lower fuel requirements associated with improved cookstoves also have positive environmental benefits. Also, the extent of deforestation can be mitigated through the use of improved cookstoves (Baldwin, 1987).

The by-products of improved cookstoves can have environmental benefits. If operated correctly, pyrolytic stoves can be made to produce activated carbon, also known as Biochar, which when used as a fertilizer can increase crop yields (Torres-Rojas et al., 2011). The use of Biochar as a fertilizer assists in the sequestration of carbon within the soil, resulting in a net reduction of greenhouse gas emissions than if it was burned directly (Lehmann & Joseph, 2009; Whitman & Lehmann, 2009).

Social benefits

Social benefits can arise from the use of improved cookstoves, as reducing the fuel requirement decreases the time required for fuel collection. This can have dramatic effects. In conflict zones, such as Darfur in Northern Sudan, it is estimated that 90% of rapes occur whilst women are collecting fuelwood outside their displaced persons camps (JWW, 2006). The use of improved cookstoves reduces fuelwood collection times, which decreases the incidence of rape - a benefit that transcends improved health outcomes (Wolf, 2005).
2.6.2 Dissemination of improved cookstoves

Large scale dissemination programs for improved cookstoves have occurred in several countries. One of the largest programs began in India in 2003. Several barriers such as limited manufacturing capacity for improved cookstoves in rural areas, a lack of knowledge regarding their use, and cultural resistance impeded uptake (Ravindranath & Balachandra, 2009).

The success or failure of a product's dissemination depends crucially on the end-user’s preferences. Health benefits are not necessarily the primary reason people decide to purchase improved cookstoves. Martin et al. (2013) find that in a Ugandan community the cost of a stove, followed by its durability were the two most important factors when purchasing a new stove. Users also reported that the major benefits of improved cookstoves were a reduction in the time spent collecting fuel, and money saved as a result of reduced fuel consumption. Health benefits were not of primary concern to end-users.

Large scale dissemination of one type of improved cookstove design is often difficult. The suitability of a stove in one region does not necessarily mean it will be successful in another. Different regions, climates, and cultural practices will impact a stove’s performance and uptake. Developing improved cookstoves should take into account region specific factors (Confino & Paddison, 2014).

2.7 Types of improved cookstoves

Many types of improved cookstoves using different operating principles are on the market today. For instance, some improved cookstoves burn a solid fuel directly, in a similar way to a three-stone fire. However the use of a chimney, in conjunction certain stove geometries, can lead to higher combustion efficiencies when compared
to traditional cookstoves. There are also stove technologies which utilise a two-stage combustion process. These stoves do not burn solid fuels directly, but instead evolve volatile matter from a solid fuel, and combust this volatile matter at a secondary location. An overview of several improved cookstoves employing different operating principles is presented in Sections 2.7.1 - 2.7.3.

### 2.7.1 Rocket stove

The Rocket cookstove is an improved cookstove which combusts a solid fuel directly. Sticks are fed into the stove and combusted. Typically, this stove has a constant cross-sectional area and insulated walls (MacCarty et al., 2008). Figure 2.3 shows a rocket stove in operation.

The rate at which sticks are fed into the combustion chamber controls the power output of the stove. The short insulated chimney acts to decrease CO emissions,
2.7.2 Top-Lit Up-Draft cookstove

Top-Lit Up-Draft (TLUD) cookstoves utilise two distinct combustion stages when extracting useful energy from solid biomass fuels. The solid biomass is first heated in a low oxygen environment. Pyrolysis at the fuel stack leads to the evolution of a gas mixture which is rich in combustible volatile compounds. These volatiles are then mixed with air at a secondary air inlet where they are combusted. The operation of a TLUD stove is illustrated in Figure 2.4.

When a TLUD stove is first lit combustion occurs directly at the fuel stack. The fuel stack shown in Figure 2.4b restricts air reaching the pyrolysis front, causing the

as it allows a region in which air and volatiles can mix, promoting more complete combustion (MacCarty et al., 2008). Significant fuel savings, of up to 40% are associated with this stove (GACC, 2014a).
The top layer of fuel to combust in a low oxygen environment. This results in incomplete combustion at the fuel stack, causing a volatile rich gas mixture to rise up through the body of the stove under natural buoyancy. Upon reaching the secondary inlet, the volatile gas mixes with air and combusts. The flame travels up the chimney and creates a pressure drop at the top, drawing in more air through both the secondary and primary air inlets (Birzer et al., 2013). The flame front remains above the solid fuel at a point near the secondary air inlets. This flame is sustained by the radiant energy from the flame heating the fuel stack, which in turn sustains the rate of release of volatiles. As the fuel is exhausted the rate of release of volatiles is eventually insufficient to sustain a flame at the secondary air inlet, causing the flame front to drop down to the fuel stack where the remaining fuel smoulders.

The gaseous fuel produced within a TLUD is able to readily mix with air prior to combustion. This is in contrast to traditional stoves that burn solid fuels directly. Two gases are able to mix more readily than a gas and a solid. This enhanced mixing promotes complete combustion, leading to higher combustion efficiencies than traditional cookstoves (Jetter et al., 2012). This advantageous feature of TLUD stove operation ceases once combustion stops at the secondary air inlet. At this point two gases are no longer mixing and then combusting. Instead a solid fuel is smouldering in a low oxygen environment, which can significant increase hazardous emissions. Therefore, TLUD stoves are intended to be extinguished once combustion ceases at the secondary air inlet.

The ratio of secondary air to primary air can be altered to optimise combustion efficiency. Altering this ratio affects the mixing which occurs between volatile gases and entrained air - which influences the completeness of combustion. Birzer et al. (2013) find that the optimum ratio for the area of the secondary air inlets to the primary air inlet to be 4:1. This ratio is based on the geometries of the primary and secondary air inlets. It is not known if the airflow entering the stove at these two inlets is subject to the same ratio.
The fuels used in a TLUD stove can range from wood chips, dung, rice husks to corn cobs (Jetter et al., 2012). The size of the fuel will influence the amount of air that is drawn up through the fuel stack to the pyrolysis front. Large fuel pieces will create gaps between them which allow the passage of air. As the fuel size decreases these gaps also decrease in size, and the airflow entering the primary air inlet is restricted. Fuel which is too small may completely block primary airflow. In this case the fuel will fail to sustain pyrolysis and the stove will be inoperable (Birzer et al., 2013). Consequently, fuel size has the potential to play a significant role in the effective operation of a TLUD stove.

**Fan assisted TLUD**

Fans can be incorporated into TLUD stove designs to improve performance by promoting better mixing of combustible gases than would occur under natural draft. Fan forced airflow is also beneficial when the fuel is too compact to allow natural airflow through the fuel stack. Forcing air into the stove reduces the reliance on the stove geometry, and the materials used to create effective TLUD stoves (Kumar et al., 2013).

**Advantages and disadvantages**

TLUD stoves are simple in design and relatively easy to use. However, considerable work must be done to optimise their emissions and energy output. The stove can be constructed from basic materials, and unlike some other semi-gasifier stoves, a TLUD does not necessarily require a fan to operate. When a TLUD stove is operating correctly, CO and particulate emissions are very low (Jetter et al., 2012). TLUD stoves can also operate for long durations. The Champion TLUD cookstove is capable of operating for over an hour with flame temperatures between 700-850° C.
However, incorrect use can potentially expose users to dangerous levels of hazardous emissions (Andreatta, 2007).

TLUD stoves are typically designed as batch burning stoves, meaning that fuel cannot be added once it has been ignited. If inadequate fuel or air is supplied, the cookstove will perform very poorly. Also, a greater proportion of emissions are released as the cookstoves run out of fuel (Andreatta, 2007). These emissions predominantly constitute CO and hydrogen, which are both extremely hazardous if inhaled in high concentrations (Zhang, 2010). This emphasises the importance of using these stoves correctly.

### 2.7.3 Vivek semi-gasifier cookstove

The Vivek cookstove is semi-gasifier cookstove which commonly runs on agricultural and industrial residues. A common fuel for a Vivek stove is sawdust. When filled to capacity, the Vivek stove operates for between 1.5 to 2 hours. This type of cookstove is currently in use in parts of India to feed families of up to five. Figure 2.5 shows a Vivek stove in operation. It can be seen in Figure 2.5 that sawdust is compacted around a central cylindrical cavity. The sawdust is heated in a low oxygen environment, which causes the release of volatile gases. A secondary air inlet entrains air which then mixes with, and facilitates the combustion of these gases (Bhanap & Deshmukh, 2012).

### 2.7.4 Co-generation

In addition to servicing heating and cooking requirements, biomass stoves can also be used to generate electricity. Electricity generating stoves are typically larger than those found in households. In some instances stoves are capable of generating enough
Figure 2.5: Vivek stove (Bhanap & Deshmukh, 2012)

electricity to service the basic energy needs of small communities (Ravindranath & Balachandra, 2009).

Semi-gasifier stoves are capable of producing gas which can be collected and used to power internal combustion engines. The collected gas can also be combusted in a boiler to generate steam to power electric turbines (Ravindranath & Balachandra, 2009). At present there is research into the integration of thermo-electric generators and photovoltaic technologies into the design of semi-gasifier cookstoves. The heat given off from the stove can be used to generate electricity which can be used to power lighting systems within households. Alternatively, small fans can force additional air into the stove, thereby increasing combustion efficiency (Kumar et al., 2013).

2.8 Current research

A number of institutions around the world are conducting research into improved cookstoves. Among these institutions are the Lawrence Berkeley National Laboratory (LBNL), The State University of Colorado, and the University of Adelaide.
These institutions are involved in the design, manufacture, and dissemination of improved cookstoves to varying degrees.

### 2.8.1 The University of Adelaide

There is ongoing research at the University of Adelaide into the design and operation of improved cookstoves. In 2011 researchers at the University began investigating the performance of several types of improved cookstoves. A Rocket stove and a TLUD stove were the main subjects of the project’s analysis. The group did not have the capacity to control airflow rates entering into their stoves; instead they were limited in their analysis to controlling geometric features of the stove designs. Therefore it was not possible to gain unbiased estimates of the relative effect a variable had on stove performance. For instance, changing the geometry of the secondary air inlet may impact the volume of air entrained, as well as the mixing characteristics of air within the stove. If the amount of air supplied cannot be fixed, it is not possible to determine the sole effect that the inlet geometry has on stove performance. An attempt to address this issue was pursued in the following year with the construction of a testing stove.

In 2012 a testing stove was constructed. A distinguishing feature of this stove is its ability to control both primary and secondary airflow rates. The stove was designed with a small fan used to control the primary airflow rate, while compressed secondary air was delivered to the stove through the narrow tubes seen protruding from the stove body in Figure 2.6. Additional stove parameters, such as the position of the fuel stack and chimney geometry, can be easily adjusted with this apparatus.

A group of final year students in 2013 were the first to use the newly constructed testing stove. The group used the stove to investigate the relative effect on emissions associated with burning different types of biomass. They also investigated how
altering the secondary airflow rate impacted the emissions evolved. Their data indicate that increasing the secondary airflow rate reduces emissions (Boerema et al., 2013). However their utilization of the testing stove was limited in scope. The group chose to pursue the construction of a modified TLUD stove instead of engaging in further research using the testing stove.

The testing stove was partially parameterised by a Masters student in early 2014. Holden (2014) investigated the relative effect that primary and secondary airflow rates have on the testing stove’s performance. The data suggest that there was no conclusive relationship between the primary airflow rate and the quantity of CO emissions evolved. However, increasing the secondary airflow rate resulted in a decrease in CO emissions. Crucially, Holden (2014) suggests that the primary and secondary airflows delivered to the current testing TLUD stove are not analogous to a real system. The delivery mechanism of secondary air through narrow tubes is not representative of a real TLUD system. Therefore modifications are likely to be required before meaningful data can be obtained.
2.8.2 Colorado State University

In 2012 the U.S. Department of Energy awarded Colorado State University a USD $1 million grant to develop an improved semi-gasifier cookstove (Colorado State University, 2012). Presently a TLUD stove is under investigation. The apparatus at the University has similar features to the testing stove designed and manufactured at The University of Adelaide. Both rigs control primary and secondary flow rates into the stove. However, the apparatus used at the Colorado State University is capable of varying additional parameters such as the temperature of secondary air entering the stove, and the geometry of the secondary air inlet. The sensors incorporated into the stove are also a point of difference. The apparatus at Colorado State University incorporates several thermocouples into its design. These sensors are capable of measuring the temperature at various locations within the stove, and can give an indication of the combustion characteristics at the fuel stack. Combustion characteristics of the flame are also studied through the use of laser diagnostics.

Preliminary testing suggests that a secondary to primary airflow rate ratio of 3:1 optimises the useful amount of energy extracted from the cookstove. Their data also suggest that the useful power output decreases as this ratio increases beyond 3:1. The rate of fuel consumption is also shown to increase as the primary airflow rate increases (Personal Communication, 2014).

2.8.3 Lawrence Berkeley National Laboratory

The Lawrence Berkeley National Laboratory (LBNL) has been involved in the research and development of several improved cookstoves. In 2005 LBNL engaged in a field study in Darfur, Northern Sudan. This field trip tested the performance of three improved cookstoves within internally displaced persons (IDP) camps. Surveys were also conducted to examine the preferences and cooking practices of stove
users within these camps (Galitsky et al., 2006).

Following the field trip to Darfur, the design and development of an improved cook-stove suitable to the region was pursued. The final design, known as the Berkeley-Darfur stove, is a modified version of a Rocket stove. The stove operates by feeding sticks into the stove’s combustion chamber, where the solid fuel is burned directly.

![Berkeley-Darfur cookstove](TEL_2014)

The Berkeley-Darfur Stove can be seen in Figure 2.7. The stove takes into account several region specific factors, such as high wind speeds and unstable terrain. A shield around the stove helps prevent the flame being extinguished by wind gusts, while base supports increase the stove’s stability when placed on uneven ground (Amrose, 2008).

At present NGOs, such as World Vision Australia, have assisted in the dissemination of the Berkeley-Darfur Stove in Ethiopia. Following feedback from users, the stove was modified to better suit local cooking practices and user preferences. This has led to the development of the Berkeley-Ethiopia Stove. Trial projects involving the dissemination and monitoring of 1,000 Berkeley-Ethiopia Stoves are currently under-
way in Ethiopia, and it is hoped this project will provide a template for future large scale improved cookstove dissemination in the region (LNBL, 2014).
Chapter 3

Project Direction

In recent years semi-gasifier cookstoves, such as TLUD stoves, have become increasingly popular. Despite several companies manufacturing TLUD stoves, there is little scientific data that can be used to optimise their design. The current project will begin to address this issue by undertaking a parametric analysis of a TLUD stove. Relationships between TLUD stove variables and corresponding changes in stove performance will be explored, and analysed to develop recommendations for the optimisation of TLUD stoves.

A purpose built testing stove constructed in 2012 was used to explore the relationship of TLUD stove variables on stove performance. The testing stove is able to independently control stove variables, such as airflow rates, and was used by previous groups to analyse the effect of primary and secondary airflow rates on stove performance. An analysis of the apparatus used, and procedures followed by these groups suggests that the airflow rates tested were significantly above natural draft, emulating the operation of a fan assisted TLUD stove. However, the testing stove’s fan-assisted operation was not compared to a configuration where the stove entrains air naturally. Therefore it was not known if incorporating a fan into the design
of a TLUD improved performance, relative to the natural draft case. The current project addresses this issue by analysing the effects of primary and secondary airflow rates on stove performance, by examining airflow rates above and below the average natural draft airflow rate. A determination of the extent to which fans improve TLUD stove operation was then made.

In addition to airflow rates, several other stove parameters have been investigated, including the location of the fuel stack within the stove relative to the secondary air inlet, and the depth of the fuel stack. The effect that the shape and size of fuel have on stove performance are also explored. Geometric stove variables, as well as types of stove materials are not examined in the current project. Variables such as the: diameter, height, shape, thickness, and material of the stove body cannot be altered without constructing a new testing stove. While geometric and material parameters are important in terms of the optimisation of TLUD stoves, they were considered outside the scope of this project.

There are inherent differences associated with the design of the testing stove and TLUD systems that are in use in developing countries. For instance, the testing stove is approximately 1.6 m tall and 206 mm in diameter, much larger than real TLUD systems. The testing stove has not been designed with the intention of precisely emulating current TLUD systems used in the field, rather its purpose is to help develop a fundamental understanding of the combustion science associated with TLUD stove operation. Acknowledging this limitation is relevant in comparing different testing stove parameter configurations.

3.1 Goals

The current project’s goal is to develop an understanding of how TLUD stove performance is affected by changing stove parameters. Additional goals relating to the
influence that fuel characteristics have on stove performance will also be explored. In addition to improving the scientific understanding of TLUD stoves, the current project also raises the profile of improved cookstove research undertaken at the University of Adelaide.

3.1.1 Primary goals

Four primary goals are defined for the current project. Firstly, the formal commissioning of the testing stove. Following commissioning, the three remaining primary goals are: establishing the effect that primary airflow rates, secondary airflow rates, and fuel size have on TLUD stove performance.

Commissioning the testing stove

The testing stove had not been formally commissioned prior to the current project. Therefore the first objective is to ascertain whether the testing stove is capable of operating as a TLUD semi-gasifier cookstove. By commissioning the stove a greater understanding of its combustion characteristics will be developed.

Primary airflow rates

The influence that primary airflow rates have on stove performance will be investigated. While this variable had been investigated by previous groups, an analysis of their testing procedures revealed the stove had been operated at airflow rates much higher than natural draft. Consequently, the conclusions drawn by previous groups were limited to the minority of TLUD stoves that are fan-assisted. The current project addresses this issue by constructing a testing range around the natural draft flow rate. The effectiveness of fans relative to a natural draft baseline will be
determined, and recommendations made regarding the incorporation of primary air inlet fans into the design of TLUD stoves.

**Secondary airflow rates**

The effect that secondary airflow rates have on stove performance will be explored. While this variable had been tested by previous groups, the secondary airflow rates were far in excess of the flow rates induced under natural draft. It was not clear if the introduction of a secondary air fan had an appreciable effect on stove performance relative to natural draft flow rates. The current project addresses this issue by controlling secondary airflow rates about the average natural draft secondary airflow rate. The effectiveness of a secondary air fan will then determined, which will lead to a recommendation regarding the incorporation of such a device.

**Fuel size**

The effect that different fuel sizes have on TLUD stove performance will be analysed. This will be achieved by comparing the combustion characteristics of three different fuel sizes using the testing stove. Recommendations regarding fuel sizes that improve TLUD stove performance will then made.

### 3.1.2 Extension goals

Extension goals aim to analyse the effect that additional stove parameters have on stove performance. These parameters are: the location of the fuel stack within the stove, the depth of the fuel stack, and the effect that different fuel geometries. A component that can be added to TLUD stove designs to provide temperature control will also be explored. The key findings from this project’s research will then used
to prepare a draft journal paper for submission.

**Fuel stack location**

The distance between the top of the fuel stack and the secondary air inlet can be altered, which may optimise stove performance in some circumstances. The results of this analysis will be used to develop recommendations regarding the importance of this parameter with respect to TLUD stove design.

**Fuel stack depth**

The amount of fuel placed within the stove will influence the primary airflow rate. As more fuel is added, the depth of the fuel stack will increase, as will the restriction imposed on primary airflow, potentially affecting stove performance. Different fuel stack depths will be investigated to ascertain the relative importance of this parameter.

**Temperature control**

A device to control the temperature output of a TLUD stove will be investigated. The device will control heat output by regulating the air passing through the fuel stack. Air can be regulated by placing disks with varying sized holes onto the fuel canister grate. Changing the number these holes will change the degree to which primary air is restricted. Figure 3.1 a schematic diagram of an example disk, and its relative position within the stove.
Figure 3.1: Schematic diagram cross-section showing the restrictor disk location
Draft journal paper

The main findings arising from the current project will be collated and used to write a draft journal paper.

Promoting TLUD stoves

The current project will raise the profile of improved cookstove research conducted at the University of Adelaide. Relationships between NGOs and the University will be developed. Community outreach through the use of social media explaining the operating principle of TLUD stoves, and the benefits associated with them will be undertaken.

3.2 Scope of stove performance measures

Several empirical measures have been considered when comparing the performance of different stove configurations. The key measures are: gaseous emissions measurements, burn-time, and a Water Boiling Test (WBT). Precedence will be given to gaseous emissions measurements when evaluating stove performance, as it is the reduction in hazardous emissions that leads to significant health benefits. The results obtained from other supplemental measures, such as burn-time, and WBTs are indicative of the suitability of the stove’s operation for the end user.

3.2.1 Emissions measurements

Several gaseous emissions from the testing stove’s operation will be analysed. They are: carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NOₓ), and
hydrogen (H$_2$). Atmospheric oxygen (O$_2$) will also be measured to assist in determining the effect dilution has on the sampled gases. Particulate matter is also an important product of incomplete combustion, however the Faculty does not possess equipment capable of measuring these emissions. Consequently, only gaseous emissions were analysed.

### 3.2.2 Steady-state burn-time

As shown in Section 2.7.2, TLUD stoves have an operating window in which fuel is combusted most efficiently. This period is characterised by combustion occurring at the secondary air inlet. Stove performance is deemed to increase as the length of time in this phase increases.

### 3.2.3 Water boiling test

A water boiling test (WBT) quantifies how effectively a stove transfers heat to water in a pot. Stove configurations that reduce boiling times and increase the heat transfer are preferred. At present there is no international standard for water boiling, however an ISO standard is in development (ISO, 2014). In lieu of an international standard several institutions have developed their own WBT procedures. A widely adopted WBT procedure is set-out by the Global Alliance for Clean Cookstoves (GACC). A single WBT conducted in accordance with GACC guidelines analyses stove performance for three modes of stove operation. First, with the stove body initially at ambient temperature, the stove is operated to heat either 2.5 kg or 5 kg of water in a pot. Once the water boils, water in the pot is replaced by water at ambient temperature. The stove is operated again, this time with the stove body initially above ambient temperature. These two tests are known as cold and hot-start tests respectively, where 'hot' and 'cold' refer to the initial temperature of the stove body.
The thermal mass of the stove can lead to considerable differences in the performance between these two tests. The third phase of testing involves maintaining the water temperature just below boiling for 45 minutes - known as a 'simmering test', and is done to simulate the cooking of dishes such as legumes (GACC, 2014b).

The current project has developed a modified WBT based on the GACC guidelines. These guidelines have been modified as a result of the limitations previously acknowledged for the testing stove. As the testing stove is not representative of a real TLUD system, conducting simmering tests to evaluate cooking performance is of little use. Similarly, the testing stove is constructed out of 8 mm thick steel, causing the stove to have a high thermal mass relative to TLUD stoves used in the field. Consequently the WBT analysis has focused on hot-start tests only. The mass of water heated has also been adjusted. Instead of heating either 2.5 kg or 5 kg of water as recommended by the GACC only 1 kg has been heated. This was done in order to compare the results from the current project to those obtained from previous groups, which had conducted WBTs with 1 kg of water. The testing procedure and water boiling calculations can be found in Appendix J.

3.3 Summary

The current project will investigate how TLUD stove performance is affected by several parameters. By analysing a number of measures, including gaseous emissions, burn-time, and heat-transfer, recommendations will be made to improve stove design. The incorporation of a device to control temperature will also be explored. The project aims to increase community awareness about the benefits of improved cookstoves, as well as engaging with relevant NGOs. Several
Chapter 4

Equipment

The cookstove that was used for all of the testing in this study was built previously by the University of Adelaide. This stove allows the independent control of certain parameters to observe the effect that controlling these have on stove performance. Modifications were made to the delivery mechanisms for primary and secondary air airflow, better allowing the testing stove to emulate natural draft conditions. A more detailed account of the cookstove and modifications made are presented in Sections 4.1 and 4.2.

4.1 Inherited design

The inherited testing stove was designed by a student at the University of Adelaide in 2012, and has been used by various groups since. The testing stove is able to control the primary and secondary airflow rates entering the stove body, the fuel stack height and chimney geometry. This allows for any combination of these parameters to be tested and analysed.
4.1.1 Stove body

The stove body, made from a large steel cylinder, is placed on-top of a steel primary air inlet chamber. Figure 4.2 shows the testing apparatus, while Figures 4.3b and 4.1 show schematics of the stove and define the stove thermocouple locations. The twelve pipes located just below the top rim of the stove are inlets for forced secondary air. Stove dimensions can be found in Appendix A.
Figure 4.2: Testing stove with primary air chamber panels removed and no chimney
4.1.2 Fuel grate

Figure 4.3 shows the fuel grate that is used to hold the fuel and alter its location within the stove. Perforations in the grate allow air to flow through the fuel. Connecting rods let it hang from the top rim of the stove, and allow it to be removed for cleaning between tests.

4.2 Testing stove modifications

To complete the goals set out in the current study it was necessary to make modifications to the testing stove. Modifications were made to the delivery mechanisms
Figure 4.4: The inherited fan that was previously used for forced primary air

for forced primary and secondary air, which allowed the stove to better emulate natural draft flow rates. A natural draft chimney was also constructed to allow the natural entrainment of secondary air. Section 4.2.1 to 4.2.2 detail the modifications that were made to the testing stove, why they were necessary, and the success of each modification.

4.2.1 Primary air set-up

Modifications to the primary air inlet have been made in this year’s project. Originally a small fan seen in Figure 4.4 was used to force primary air into the stove. The fan had a controllable dial to vary the fan speed, thereby altering the airflow rate entering into the stove. This fan was unable to replicate flow rates similar to what would occur under natural draft. On the lowest fan speed, the flames emanating from the stove were much higher than what was observed under natural draft.

The fan from the inherited testing stove was replaced by a compressed air supply with a needle valve and flow meter installed in the line. A compressor within the
laboratory delivered pre-dried air at 650 kPa to the testing stove. This allowed for a controllable, accurate, and measurable airflow rate to be delivered to the stove. Details of the flow meter and float used can be found in Appendix A. Figure 4.5 shows the plate that connects the compressed air to the primary air inlet chamber.

![Compressed air fitting for primary air inlet](image)

Figure 4.5: Compressed air fitting for primary air inlet

To reduce the swirling that was caused by air entering the stove through a localised position a diffuser was constructed. The diffuser can be seen in Figure 4.6 and it was installed pointing downwards to reduce the swirling and velocity of the air by more evenly distributing it within the primary air chamber before it moves into the stove. This set-up accurately modelled the natural conditions.

### 4.2.2 Secondary air set-up

The inherited forced secondary air set-up used a compressed air supply to deliver controllable and measurable secondary airflow to the stove. This air fed into the top of the stove via twelve small diameter pipes which can be seen in Figure 4.2. This delivery mechanism was improved upon by constructing a diffuser chimney, and a new chimney was also built to allow for the natural entrainment of secondary air. A detailed discussion regarding these modifications can be found in Appendix A.
CHAPTER 4. EQUIPMENT

Figure 4.6: Primary air diffuser

Chimney used for natural draft testing

The inherited testing stove initially had no capacity to entrain secondary air under natural draft. To overcome this a new chimney was built. This chimney can be seen in Figure 4.7 and has slits cut around the base, allowing air to be drawn into the chimney naturally. This chimney was proven to work after a few tests and provided enough air at the secondary inlets to allow for combustion this can be seen in Figure 4.8. Further details regarding the dimensions of this chimney can be found in Appendix A.
Figure 4.7: The chimney that was used for all natural buoyancy tests

Figure 4.8: Combustion at secondary air inlet
Controlled secondary airflow velocities

A diffuser was built to ensure that the forced secondary air was representative of natural draft airflow. The inherited design fed air into the stove through small diameter pipes that caused the air to be released at a high velocity. These air jets impinged in the center of the stove and forced air down the stove towards the fuel grate and was not an accurate representation of the natural draft. The design for the secondary air diffuser was modelled on the natural draft chimney mentioned in Section 4.2.2. The diffuser shown in Figures 4.9 and 4.10 works by slowing the velocity of compressed air by filling a small box before it enters the chimney. This device allows for a more even distribution of air - better representing natural draft airflow. It still has a small amount of swirl and the swirl effect can be seen in Figure 4.11 at the highest flow rate that testing was conducted at. This small amount of swirl is minimal when compared to the effects that were caused by the original system. The CAD drawings of the diffuser are attached in Appendix K and details regarding the secondary air diffuser can be found in Appendix A.
CHAPTER 4. EQUIPMENT

Figure 4.10: A schematic diagram showing the basic dimensions of the secondary air diffuser

Figure 4.11: Wool hanging in the chimney shows the difference in the swirl between 0 and 574 L/min
4.2.3 Summary of modifications

Many modifications have been made to the inherited testing stove. These modifications include the design of a chimney to allow the testing stove to entrain secondary air under natural draft conditions. The delivery mechanisms for controlled airflows are also modified. The fan which originally controlled primary airflow entering the testing stove was replaced with a measurable and controllable compressed air setup. A new mechanism to deliver controlled secondary airflow to the stove was also developed. Both of these modifications resulted in controlled airflows which better represent the entrainment of air under natural draft.

4.3 Data collection

Emissions data were collected using a Testo 350XL gas analyser, and temperature data were collected using two 3.5 mm K-type sheathed thermocouples. The relative locations of these devices is shown in Figure 4.12. Further detail on data collection apparatus can be found in Appendix A.
Figure 4.12: A diagram showing the data collection set-up
Chapter 5

Commissioning

The testing stove has been subjected to a commissioning process which establishes its capability to operate as a TLUD stove. This involved analysing emissions and temperature data generated as a result of the stove’s operation, as well as photographic evidence. The data was then compared to the expected operating characteristics of a TLUD stove, and suggests the testing stove is capable of operating as TLUD stove.

5.1 Fuel selection

The representative nature of the fuel to be combusted, as well as experimental considerations were taken into account when selecting a fuel. Wood is the most commonly combusted fuel in the developing world, so it is sensible to use a wood-based fuel. It is also desirable to combust a fuel with a high surface area, emulating the physical characteristics of twigs or sticks commonly used. Bark chips satisfy both criteria, and have the added benefit of being supplied in batches where the chip size is approximately constant. This assists in controlling for the fuel size when
conducting testing. These determinants led to the selection of Jeffries PlayScape bark chips when commissioning the stove.

5.2 Stove configuration and procedures

Prior to commissioning, the testing stove had only been operated using forced primary and secondary airflows. Consequently, it was not known if the stove was capable of operating as TLUD when entraining air naturally. The commissioning phase of testing addressed this issue by observing the stove’s performance when entraining air under natural draft. This was accomplished by removing the bottom panels of the primary air inlet, thereby allowing the entrainment of primary air from all directions. Similarly, a chimney with three slots cut into it allowed the natural entrainment of air at the secondary air inlet. The natural draft stove configuration is shown in Figure 5.1.
The temperature of the stove body at the time of ignition can impact on the combustion characteristics of a fuel. For reasons set-out in Section 3.2, the current project will limit its analysis to hot-start tests. The stove body temperature at which the stove was lit was carefully considered. From Section 2.3.1 it is known that woodfuels devolve into volatile products at approximately 200° C. Therefore fuel should be loaded into the stove when the stove body is below 200° C in order to prevent premature de-volatilisation.

An infra-red thermometer was used to measure the temperature of the stove body at location C shown in Figure 4.12. Fuel was only loaded into the stove once the temperature at location C was below 150° C, thereby mitigating the risk of premature de-volatilisation. For each test 700 g of Jeffries PlayScape bark chips was loaded into the stove. The chimney was then positioned on the stove and 10 mL of methylated spirits was poured onto the bark chips. The stove was ignited when the temperature at location C reached 130° C. This was accomplished by placing a burning piece of...
paper towel on the fuel stack. Appendix B outlines the experimental procedure for this phase of testing in detail.

5.3 Data collection

Emissions and temperature data are collected, with mean temperature measurements taken using sleeved K-type thermocouples at locations A and B. Location B measures the temperature of pre-combusted volatile gases emanating from the fuel stack, while location A measures the temperature of the combusted volatile gases within the chimney.

A gas analyser is used to sample emissions evolved from the stove. The gases sampled are: carbon monoxide (CO), carbon dioxide (CO$_2$), nitrogen oxides (NO$_X$), hydrogen (H$_2$), and oxygen (O$_2$). The sampling probe’s location attempted to follow apparatus protocols established by the Global Alliance for Clean Cookstoves (GACC, 2014b). The GACC recommends that emissions be sampled from within the flue of extracted gases. This would require the drilling of a hole into the flue to allow the insertion of the Testo probe. It was not possible to arrange the drilling of this hole; instead, the probe was placed as close as practicable to the flue’s entrance. The probe was situated 1.18 m from the top of the stove body, with the tip of the probe placed over the centreline of stove body. Figure 4.12 shows the relative position of the probe to the stove body.

5.4 Testing stove operation

The testing stove’s operation is observed and compared to the expected operation of a TLUD stove. Photographic evidence, as well as emissions and temperature data
suggest that the testing stove is capable of operating as TLUD stove.

5.4.1 Expected TLUD stove operating characteristics

The operation of a TLUD stove can be characterised by three distinct phases of combustion.

1. When the stove is lit, combustion occurs directly at the fuel stack. Initially, oxygen within the stove is consumed, and the fuel begins combusting in a low oxygen environment. As the fuel stack temperature increases, the rate of release of volatiles from the fuel increases. These volatile products rise up the stove body to the secondary air inlet. Upon reaching a sufficiently high concentration, an ignition source, such as the flame from the fuel stack, initiates combustion at the secondary air inlet.

2. The onset of combustion at the secondary air inlet signifies that the stove has transitioned to the second phase of combustion. Radiant heat from the flame heats the fuel stack, thereby sustaining the rate of release of volatiles, which in turn sustains the flame at the secondary air inlet. The mixing of a partially gasified fuel with air results in high combustion efficiencies relative to the initial phase. This phase constitutes the ideal operating window for TLUD stoves. The stove continues to operate in this phase until volatile matter within the fuel is diminished significantly. As the fuel is exhausted, the rate of release of volatiles is insufficient to sustain combustion at the secondary air inlet. The flame then extinguishes at the secondary air inlet leading to the onset of the final phase of combustion.

3. The final phase of combustion is characterised by fuel smouldering within the stove body, decreasing combustion efficiency relative to the second phase of combustion.
CHAPTER 5. COMMISSIONING

The differences in combustion efficiencies between phases can be observed by analysing incomplete products of combustion, such as carbon monoxide.

### 5.4.2 Photographic evidence

Photographic evidence strongly suggests that the testing stove is capable of operating as a TLUD stove. The chimney has been removed in Figure 5.2 to better illustrates how volatile gases combust when mixing with air. The thick white smoke emanating from the stove in Figure 5.2a constitutes the volatile gases evolved from the fuel stack. These gases mix with air and then combust as shown in Figure 5.2b. This strongly suggests that the testing stove is operating as a TLUD stove. An analysis of the emissions and temperature data support this finding.

### 5.4.3 Emissions data

Variations in combustion efficiency are revealed by analysing changes in the products of incomplete combustion, such as CO, over the course of the combustion cycle. Figure 5.3 shows how CO varies over the course of eight tests, containing three distinct features which are expected of TLUD stove operation. The CO peak observed in the initial phase is consistent with combustion occurring directly at the fuel stack. The distinct drop in CO emissions after the initial peak results from the flame transitioning to the secondary air inlet, which increases the combustion efficiency relative to the initial phase. CO emissions remain approximately constant until 400 s. At this point in time the fuel is almost exhausted of volatile matter, and a flame can no longer be sustained at the secondary air inlet. The flame recedes into the stove body, and combustion again occurs directly at the fuel stack. This results in a CO peak in the final phase. The three features observed in Figure 5.3 are consistent with the expected operation of a TLUD stove as described in Section 5.4.1.
Figure 5.2: Combustion of volatile gases evolved from pre-heated fuel
5.4.4 Temperature data

Temperature data suggests that the testing stove operates as a TLUD stove. Figure 5.4 shows the mean temperature traces for the volatile gases pre and post combustion. Dotted red traces represent the mean temperature of volatile gases post-combustion within the chimney, and blue traces represent the mean temperature of the pre-combusted volatile gases within the stove. In the initial phase, combustion occurs at the fuel stack, and the flame front is directly beneath location B in Figure 4.12, causing the inside stove temperature to rise rapidly. However in the second phase combustion transitions to the secondary air inlet, causing the flame front to be above location B. During this phase the temperature of gases within the chimney are approximately 150° C hotter than the gases within the stove body - further evidence that combustion is occurring predominantly at the secondary air inlet. This is consistent with the expected operation of a TLUD stove.
5.4.5 Summary

There is strong evidence to suggest that the testing stove is capable of operating as a TLUD stove. Photographic evidence is consistent with the expected operation of TLUD stove. An analysis of trends associated with emissions and temperature data also supports this finding.
Chapter 6

Benchmarking

A benchmarking phase of testing was undertaken prior to analysing the impact that stove parameters have on stove performance. First, a suitable type and mass of fuel was determined. A final selection of 700 g of Jeffries PlayScape bark chips was made, and procedures developed to control the fuel’s moisture content. The testing stove’s operation under natural draft airflows was then analysed. The emissions and temperature data obtained form a benchmark against which future tests can be compared, making it possible to ascertain how altering a parameter affects stove performance relative to the natural draft baseline.

6.1 Stove configuration

In this configuration, the introduction of primary and secondary air was not controlled, and entered through openings in the stove body. Figure 5.1 shows the stove in this configuration.
6.2 Fuel selection

The shape, size, and type of a biomass fuel will influence its combustion characteristics, and therefore must be controlled when undertaking an analysis of stove parameters. As discussed in Section 5.1 bark chips are a reasonable representation of the types of biomass predominantly used in the developing world. The size of bark chips in a batch is relatively uniform, which is desirable when attempting to control the fuel size. These two factors led to the decision to use bark chips as the primary fuel for the current project.

Bark chips on the market differ in their composition, size, and price. Three types of bark chips have been tested for their suitability. These are Radiata pine chips, Tatura pine chips, and Jeffries PlayScape bark chips. The relative shape and size of these bark chips is shown in Figure 6.1.
6.2.1 Type of bark chips

It is desirable to use a fuel that has consistent combustion characteristics. This better allows the determination of the true effect of altering a stove parameter on stove performance. A proxy measure for the repeatability of combustion is the temperature of the volatile gases within the stove body. Inconsistent combustion at the fuel stack will cause large fluctuations in the temperature of these gases, resulting in noisy temperature traces.

The mean temperature of pre-combusted volatile gases was measured at location B for each bark chip type. These temperature traces are shown in Figure 6.2. Tatura pine chips and Jeffries PlayScape bark chips showed considerable repeatability in their temperature traces, while Radiata pine chips showed limited repeatability between tests. The availability of supply of these fuels is also a point of difference. Jeffries PlayScape bark chips could be sourced locally and more cheaply than Tatura pine chips from Victoria. This led to the selection of the locally sourced bark chips as the primary fuel for current the project.

6.2.2 Moisture content

The pyrolysis of wood is influenced by moisture content (Gray et al., 1985). In order to control moisture content, bark chips were placed in an enclosure and dried using an air-conditioner. The temperature in the enclosure was kept constant at 37 °C for 16 hours. Further details regarding the drying procedure can be found in Appendix C.1. Following the drying procedure, an ASTM standard was used to determine the moisture content of the bark chips (ASTM, 2003). This was calculated on a dry mass basis using Equation 6.2.1, in accordance with the ASTM standard. This procedure resulted in the bark chips having a moisture content of approximately 7%, meaning reduced variability in the moisture content of the fuel between tests.
Figure 6.2: Temperature of pre-combusted volatiles within the stove for different bark chips
The drying procedure leads to greater repeatability in the temperature profiles of the pre-combusted volatile gases, as shown in Figure 6.3. The temperature profiles of dried bark chips exhibit greater repeatability than un-dried chips, suggesting that the drying procedure leads to greater consistency of the combustion characteristics of the fuel. This drying procedure for all tests using bark chips.

6.2.3 Mass of fuel

A suitable mass of fuel to be combusted for each test was determined. It was found that 700 g was most suitable for the current project. This mass resulted in the three stages of TLUD stove operation being observed, while keeping test times to a reasonable duration.

A mass of 700 g of bark chips combusted in approximately 15 minutes. This burn-time is significantly shorter than what would be required of a real TLUD system.
in the field. However, as stated in the introduction to Chapter 3, the testing stove has been developed specifically to understand the combustion science associated with TLUD stove operation, rather than replicate a TLUD system used in the field. Accordingly, the short burn-time was deemed acceptable, as it was still possible to observe the three stages of combustion associated with TLUD stove operation.

6.3 Benchmark testing

The testing stove is operated using a natural draft configuration as described in Section 6.1. A total of eight repeat tests were conducted in the benchmarking phase of testing. Emissions and temperature data are recorded, and the results form a basis against which future controlled airflow rate tests can be compared.

6.3.1 Emissions

For each benchmarking test five different emissions are recorded: carbon monoxide (CO), carbon dioxide (CO$_2$), hydrogen (H$_2$), nitrogen oxides (NO$_X$), and oxygen (O$_2$). The emissions data undergoes a normalization procedure to take into account dilution effects. The normalized emissions profiles are then split into the three different stages of combustion using decision rules generated in Matlab. Data in each phase is analysed, and summary statistics are generated.

Normalization

External factors, such as the air-conditioning system within the laboratory, resulted in variable dilution of the sampled gases. In order to account for this variability, the sampled gases underwent a normalization procedure. Emissions are normalized on
a molar basis against the total carbon content of the sampled gases. A reasonable proxy for the total carbon content is the sum of CO and CO$_2$ (Gray et al., 1985). A normalized measure is obtained by dividing the sampled emissions by the sum of CO and CO$_2$ at each sampling interval. Equation 6.3.1 shows the construction of a normalized measure of CO$_2$ emissions.

$$\text{Normalized CO}_2 = \frac{\text{CO}_2}{\text{CO} + \text{CO}_2} \quad (6.3.1)$$

The measure shown in Equation 6.3.1 is widely accepted in the literature, and is known as a modified or nominal combustion efficiency (Jetter & Kariher, 2009; Johnson et al., 2010; Smith, Uma, Kishore, Lata, Joshi, Zhang, Rasmussen & Khalil, 2000). It is refereed to as a modified measure because it only takes into account two carbon based emissions - particulate matter and unburned hydrocarbons are excluded. The true combustion efficiency is calculated by finding the ratio of the products of complete combustion relative to the total products of combustion. It has been shown that the modified measure expressed in Equation 6.3.1 is a reasonable approximation for the true combustion efficiency (Gray et al., 1985). All sampled emissions undergo this same normalization procedure to take into account dilution effects.

**Emissions profiles**

Normalized and non-normalized emissions traces are shown in Figure 6.4. Oxygen traces are also presented also give an indication of the stoichiometry of the sampled gases. Significant variability is observed in the initial and final phases of combustion for all the normalized plots. However, between 170 s and 400 s the normalized measures of the sampled gases remain approximately constant. It is in this steady-state phase of combustion that the testing stove is operating as a TLUD stove.
Relationships between emissions in the steady-state phase can be observed. Figures 6.4b and 6.4d show that a correlation exists between the presence of CO and unburned H\(_2\). Both CO and H\(_2\) are major constituent products of pyrolysed biomass (Lv et al., 2007). An increase in these emissions is the result of volatile gases being combusted incompletely. In the steady-state phase, combustion occurs at the secondary air inlet - resulting in higher combustion efficiencies relative to the initial and final phases, where combustion occurs directly at the fuel stack. Therefore fewer products of incomplete combustion, such as CO and H\(_2\), will be evolved in the steady-state phase relative to the initial and final phases. This gives rise to the shape and correlation between the CO and H\(_2\) emissions traces shown in Figures 6.4b and 6.4d respectively. The same trend is observed in Figure 6.4f which shows the modified combustion efficiency (MCE) of the stove’s operation. In the initial and final phases, the efficiency decreases, whereas the MCE is high during the steady-state phase when combustion is occurring at the secondary air inlet.

During the steady-state phase of combustion normalized NO\(_X\) emissions are seen to remain approximately constant. This is unsurprising as the NO\(_X\) are typically related to the temperatures generated within the stove. It can be seen in Figure 6.7 that the chimney temperature in the steady-state phase is also approximately constant. Therefore the rate at which nitrogen and oxygen within the atmosphere to form NO\(_X\) is also expected to be approximately constant in this phase.

(a) Non-normalized CO Traces

(b) Normalized CO Traces
CHAPTER 6. BENCHMARKING

(c) Non-normalized H$_2$ Traces

(d) Normalized H$_2$ Traces

(e) Non-normalized NO$_x$ Traces

(f) Normalized NO$_x$ Traces

(e) Non-normalized CO$_2$ Traces

(f) Normalized CO$_2$ Traces
Different features of the emissions profiles are of interest in each combustion phase. In the initial phase it is instructive to determine the peak values of CO and H$_2$ evolved, as well as the times at which these peaks occur. In the steady-state phase peak values are not observed - instead, emissions remain approximately constant and the average value, known as the Time Weighted Average (TWA), is determined. In the final phase peak values of CO and H$_2$, as well as TWAs for all emissions are calculated. In order to extract these metrics from the data, each emissions profile is separated into the three distinct phases of combustion associated with TLUD stove operation.

Emissions data are separated into phases by analysing the normalized CO traces generated from each test. The rate of change of this profile can be used to estimate the time at which transition from one combustion phase to another occurs. Figure 6.5b shows the derivative of the normalized CO emissions trace shown in Figure 6.5a. The rate of change of normalized CO decreases after then initial peak, and is approximately zero when operating in the steady-state phase of combustion. A decision rule has been developed in Matlab which identifies the time after the
initial peak when combustion transitions to the steady-state phase. The rule determines the time when the rate of change of CO first becomes less than 0.002 s\(^{-1}\) after the initial peak. This time is indicated in Figure 6.5 by a dashed line vertical line at approximately 100 s. The onset of the final phase is found in a similar way. After the onset of the steady-state phase, the time at which the rate of change of CO exceeds 0.002 s\(^{-1}\) is found. This time is used to indicate the onset of the final phase of combustion, and is represented by a vertical dashed line at 400 s in Figure 6.5.

The time intervals found using the decision rules can then be applied to the original normalized CO trace. This is shown in Figure 6.6, where the different colours are automatically generated by the decision rules. It can be seen that the rules effectively separate the data into the three distinct phases of combustion. The red, blue and yellow sections represent the initial, steady-state, and final phases of combustion respectively. Data analysis can then be carried out on each phase.

The data analysis procedure culminates in the generation of Table 6.2, which shows the normalized emissions metrics generated from benchmarking testing. The metrics in the left column of Table 6.2 are calculated for each test. The mean of these metrics for each test is found, and is used to populate Table 6.2. The bracketed values represent the standard deviation associated the mean value for each metric. The data in this table serves as a basis of comparison against which future tests can be compared.

### 6.3.2 Stove temperatures

The temperatures generated at two stove locations are recorded. Thermocouple locations A and B shown in Figure 4.12 measure the mean temperature of the post and pre combusted volatile gases respectively. The temperature profiles generated at these locations are shown in Figure 6.7.
## Benchmarking

<table>
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<th></th>
<th>Initial</th>
<th>Steady-State</th>
<th>Final</th>
</tr>
</thead>
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<td></td>
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<td>(28.6)</td>
<td>(17.1)</td>
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<td>—</td>
<td>99.2</td>
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<tr>
<td></td>
<td>(40)</td>
<td>—</td>
<td>(24.3)</td>
</tr>
<tr>
<td>Time to CO Peak [s]</td>
<td>52.5</td>
<td>—</td>
<td>531</td>
</tr>
<tr>
<td></td>
<td>(11.4)</td>
<td>—</td>
<td>(48.5)</td>
</tr>
<tr>
<td>Max H$_2$ Peak $[-] \times 10^3$</td>
<td>12.1</td>
<td>—</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>(10.8)</td>
<td>—</td>
<td>(6.29)</td>
</tr>
<tr>
<td>Time to H$_2$ Peak [s]</td>
<td>71.1</td>
<td>—</td>
<td>537</td>
</tr>
<tr>
<td></td>
<td>(11.8)</td>
<td>—</td>
<td>(39.8)</td>
</tr>
<tr>
<td>TWA - CO $[-] \times 10^3$</td>
<td>—</td>
<td>3.5</td>
<td>45.3</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(0.608)</td>
<td>(10.1)</td>
</tr>
<tr>
<td>TWA - CO$_2$ $[-] \times 10^3$</td>
<td>—</td>
<td>997</td>
<td>955</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(0.608)</td>
<td>(10.1)</td>
</tr>
<tr>
<td>TWA - NO$_x$ $[-] \times 10^5$</td>
<td>—</td>
<td>59.2</td>
<td>41.2</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(4.77)</td>
<td>(10.1)</td>
</tr>
<tr>
<td>TWA - O$_2$ $[-]$</td>
<td>—</td>
<td>7.31</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(1)</td>
<td>(8.42)</td>
</tr>
<tr>
<td>TWA - H$_2$ $[-] \times 10^5$</td>
<td>—</td>
<td>16.4</td>
<td>3.54</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(18.2)</td>
<td>(1.85)</td>
</tr>
</tbody>
</table>

Table 6.2: Normalized benchmarking data
Three metrics associated with temperature are found for each test. These are: the initial peak temperature of pre-combusted volatiles in the initial phase, the minimum temperature of pre-combusted volatiles in the steady-state phase, and the maximum temperature observed within the chimney. The mean and standard deviation of the metrics for each test were found and tabulated. These temperature results can be
CHAPTER 6. BENCHMARKING

Figure 6.7: Mean temperatures of volatile gases pre and post combustion found in Appendix L.

6.4 Summary

Preliminary testing was undertaken to determine the type and mass of fuel to be used for the current project. A final selection of 700 g of Jeffries PlayScape bark chips was made, and a drying procedure was developed to reduce the variability in this fuel’s moisture content. Eight repeat tests were conducted in order to benchmark the stove’s operation when operating under natural draft. A data analysis procedure involving the normalization, as well as the separation of sampled emissions into distinct combustion phases was developed. The resulting tabulated metrics form a basis against which controlled parameter testing can be compared.
Chapter 7

Effect of Primary Airflow

A number of TLUD stoves on the market today utilise fans to increase primary airflow rates. These units are typically more expensive to purchase than TLUD stoves that operate under natural draft. Currently there is little scientific analysis pertaining to the effect that primary airflow rates have on stove performance, so it is not known if these more expensive units deliver enhanced stove performance. To address this, the testing stove’s performance was analysed for varying primary airflow rates, leading to recommendations regarding the inclusion of fans into TLUD stove designs. It was found that increasing the primary airflow rate above natural draft decreased normalized CO emissions in the initial phase of combustion. During the steady-state phase little improvement was observed. In the final phase normalized CO emissions are shown to increase with increasing primary airflow rates. This brings into question the usefulness of fans incorporated into TLUD stove designs.
7.1 Stove configuration

The primary airflow rate is controlled, and secondary air is entrained naturally through openings in the chimney. The stove configuration is shown in Figure E.1, with details found in Appendix E.

7.2 Methodology

Many stoves used in the developing world entrain air naturally through openings in the stove body. In order to determine the effectiveness or primary air fans incorporated into TLUD stove designs it is necessary to control primary airflow about the natural draft rate. The effect of increasing airflow relative to the natural draft can then be determined, giving an insight into the effectiveness of primary air fans incorporated into TLUD stove designs.

Direct measurement of the natural draft primary airflow rate using a vane anemometer was pursued in the first instance. The velocity of air entrained was insufficient to register a reading for an anemometer with a minimum flow sensitivity of 0.8 m/s. The use of devices with greater sensitivity, such as hot-wires, were advised against by staff in the Electronics Workshop - the primary reasons being the ease with which the device could be damaged by falling ash from the stove, and the difficulty associated with calibrating the device in such close proximity to an extractor hood above the stove.

The failure of the vane anemometer to register a reading did provide an upper bound for the natural draft primary airflow rate. When measuring with the vane anemometer, the primary air inlet opening was $9.2 \times 10^{-3}$ m$^2$. The upper bound for the velocity was assumed to be the minimum sensitivity of the vane anemometer, which is 0.8 m/s. These values result in an upper bound for the natural draft...
primary airflow rate of 480 L/min.

In lieu of direct measurements for the natural draft primary airflow rate, an indirect method of approximation was developed. The approach examined TLUD stove operation from first principles, and identified two stove metrics which are correlated with the primary airflow rate - the mean normalized CO concentration, and the minimum temperature of pre-combusted volatiles in the steady-state phase. The primary airflow rate was varied, and the correlated metrics were compared to results obtained from natural draft testing undertaken in Section 6.3.1. Controlled airflow rates resulting in metrics systematically above and below the natural draft metric were identified, and suggest that the average natural draft airflow rate resides within these airflow bounds. Two intermediate airflow rates at equally spaced intervals were selected within these bounds, and repeat tests were undertaken at each airflow rate. Data was then analysed in the same way as set out Section 6.3.1. Measures obtained from this analysis have been plotted against airflow rate for each stage of combustion, and the results are compared to the natural draft case. A determination was then made regarding the effect that varying the primary airflow rate had on stove performance.

7.2.1 Limitations

The indirect method of primary airflow rate approximation used does not take into account the variable nature of airflow entrainment under natural draft. A TLUD stove will entrain primary air at different flow rates over the course of the combustion cycle. In the initial phase, the fuel stack is at its maximum depth, therefore the restriction imposed on primary airflow is also at a maximum. As the fuel stack diminishes in size the restriction decreases, resulting in the airflow rate increasing. This effect, in conjunction with variations in natural buoyancy, contributes to the stove entraining air at a variable rate. This is in contrast to the indirect method
of approximation, where the primary airflow rate is constant at all stages of the combustion cycle. Therefore the indirect method employed only gives an indication of the average natural draft primary airflow rate entering the stove over the course of the combustion cycle.

7.3 Primary airflow rate bounds

An iterative approach was undertaken to determine the primary airflow rate testing bounds. This involved selecting an airflow rate and then conducting three repeat tests. The temperature and emissions data generated from these tests were then compared to the natural draft case.

The temperature of pre-combusted volatiles within the stove body, as well as the emissions evolved are influenced by the primary airflow rate. As the primary airflow rate increases more oxygen is supplied to the fuel stack, leading to a greater proportion of combustion occurring directly at the stack. This increases the temperature of pre-combusted volatiles within the stove. Therefore it is expected that the minimum temperature reached by these gases in steady-state will increase as the primary airflow rate increases. This expected behaviour, based on first principles, is supported by experimental data. Figure 7.1 shows how the minimum temperature of the pre-combusted volatile gases in the steady-phase varies for different airflow rates. The dashed line indicates the same measure obtained when the stove is operating under natural draft. The two flow rates of 78 L/min and 138 L/min encompass the natural draft measure, suggesting that an average value for the natural draft flow rate resides within these bounds. A flow rate of 118 L/min appears to be a reasonable approximation for the average natural draft primary airflow rate.

Analysis of the mean normalized CO emissions evolved in steady-state present an alternative approach to establishing testing bounds. Figure 7.2 shows how the mean
Figure 7.1: Minimum steady-state temperature of pre-combusted volatile gases for varying primary airflow rates

normalized CO emissions in steady-state vary for airflow rates between 78 L/min and 138 L/min. The dashed line in Figure 7.2 represents the equivalent measure obtained under natural draft. The controlled airflow rate bounds of 78 L/min and 138 L/min result in mean normalized CO concentrations in steady-state encompass the equivalent natural draft measure. This suggests that the average natural draft flow rate resides within these controlled airflow bounds. Upon establishing the upper and lower bounds of 78 L/min and 138 L/min respectively, two intermediate airflow rates equally spaced within these bounds were selected, resulting in a final testing range of 78, 98, 118, and 138 L/min.

7.4 Results

Emissions and temperature data reveal relationships between the primary airflow rate and several measures of stove performance. The data suggest that increasing
CHAPTER 7. EFFECT OF PRIMARY AIRFLOW

Figure 7.2: Mean normalized CO emissions in steady-state for varying primary airflow rates.

The primary airflow rate above the natural draft leads to little improvement in terms of combustion efficiency. This brings into question the effectiveness of primary air fans in TLUD stove designs.

7.4.1 Error analysis

The flow meter used for primary air testing delivered a maximum flow of 196 L/min with an accuracy of 0.4% of the maximum flow rate. However, variations in pressure within the flow meter were observed over the course of each test. This resulted in the float within the flow meter drifting from the target value. An error of ±2% of the maximum flow rate was deemed appropriate to take into account this drift, resulting in an error of ±3.92 L/min being associated with all primary airflow rate tests.


Figure 7.3: Mean normalized peak CO in initial phase for varying primary airflow rates

7.4.2 Emissions

Initial phase

Increasing the primary airflow rate is shown to have a positive effect on stove performance in the initial phase. The magnitude of the normalized CO peak, and the burn-time in the initial phase decrease with increasing airflow rates. These trends are shown in Figures 7.3 and 7.4 respectively. As greater airflow is supplied to the fuel stack in the initial phase the combustion efficiency increases - resulting in lower normalized CO peaks. Similarly, the increasing oxygen supplied assists in the spread of combustion over the entire fuel stack when the stove is first lit, decreasing the time before the onset of the steady-state phase of combustion. Both of these relationships suggest that increasing primary airflows in the initial stages of combustion improves stove performance.
Steady-state phase

Increasing primary airflow above natural draft is shown to have a marginal effect on combustion efficiency in the steady-state phase. Figure 7.5 shows the mean normalized CO$_2$ emissions in the steady-state phase for varying airflow rates, with the natural draft case represented as a dashed horizontal line. As discussed in Section 6.3.1 normalized CO$_2$ emissions are a reasonable approximation for the true combustion efficiency of a stove. Therefore Figure 7.5 suggests that increasing primary airflow above natural draft has very little effect on combustion efficiency. However it is clear that throttling the flow rate below natural draft decreases combustion efficiency, worsening stove performance.

Figure 7.6 represents the mean normalized NO$_X$ emissions evolved in the steady-state phase, and suggests that NO$_X$ emissions plateau as the primary airflow rate increases. This trend is also consistent with the relationship observed in Figure 7.10 which represents the maximum temperature generated within the chimney for varying primary airflow rates. It is known that temperature is a determinant of NO$_X$
CHAPTER 7. EFFECT OF PRIMARY AIRFLOW

Figure 7.5: Mean normalized CO₂ emissions in steady-state for varying primary airflow rates

formation, suggesting that the variations in NOₓ emissions observed are mostly attributable to changes in the temperature of volatile gases post combustion within the chimney.

The benefits arising from TLUD stove use are realised in the steady-state phase of operation, making it desirable to prolong this phase. Figure 7.7 represents the mean duration in the steady-state phase for various primary airflow rates. Figure 7.7 suggests that controlled primary airflow rates above 78 L/min decrease the duration of the steady-state phase relative to the natural draft configuration, which is represented by a dashed horizontal line. The natural draft configuration outperforms all airflow rates tested with respect to this measure, suggesting that the incorporation of a fan into TLUD stove designs will lengthen the TLUD stove’s ideal operating phase.
CHAPTER 7. EFFECT OF PRIMARY AIRFLOW

Figure 7.6: Mean normalized NO$_x$ emissions in steady-state for varying primary airflow rates

Figure 7.7: Mean time in steady-state phase for varying primary airflow rates
Final phase

Figures 7.8 and 7.9 represent the mean normalized CO evolved in the final phase and the average magnitude of the normalized CO peak in the final phase respectively. Both measures are shown to increase as the primary airflow rate increases above natural draft, worsening stove performance with respect to these two measures.

At low airflow rates there is little variation in both the magnitude of the final CO peak, and the mean CO evolved in the final phase. However, above 98 L/min both measures increase as the airflow rate increases. Above 118 L/min the natural draft baseline is surpassed for both measures. This trend may be due to the behaviour of burning char in the final phase of combustion. High airflow rates are better able to sustain char combustion than low airflow rates, which in turn leads to the evolution of additional CO in the final phase. This result suggests that the use of a fan to increase primary airflow will increase CO emissions in the final phase.
CHAPTER 7. EFFECT OF PRIMARY AIRFLOW

7.4.3 Temperature

The temperature of the pre-combusted volatiles is shown to be systematically influenced by the primary airflow rate. Figure 7.1 represents the minimum temperature of pre-combusted volatiles during the steady-state phase of combustion. The data suggest that a linear relationship exists between this measure and the primary airflow rate. This result is consistent with the hypothesis that higher primary airflow rates will increase the proportion of combustion occurring at the fuel stack, potentially resulting in less gasification, causing the testing stove to behave less like a TLUD stove.

Figure 7.10 represents the maximum chimney temperature for different primary airflow rates. A flow rate of 78 L/min results in a mean chimney temperature which is 20° C (3.8%) less than that observed for a flow rate of 98 L/min. Importantly, the maximum chimney temperature varies little when airflow exceed 98 L/min. This suggests the incorporation of a fan will have minimal effect on the temperature of
the volatile gases post-combustion.

### 7.4.4 Water boiling tests

Figure 7.13 shows the heat energy transferred to a water in a pot for varying primary airflow rates. The dashed horizontal line represents the equivalent measure obtained from natural draft testing, and suggests that the natural draft airflows transfer a greater amount of heat than the controlled primary airflow rates tested. The maximum temperature reached by the water for different airflow rates follows a similar trend, and is shown in Figure 7.11. It is evident in both figures that throttling airflow below natural draft results in a decrease in the heat transfer, and the maximum water temperature reached. It should be noted that some water temperatures in Figure 7.11 exceed 100°C, which may be attributable to the thermocouple used coming in contact with the bottom of the pot.
Figure 7.11: Maximum water temperature for varying primary airflow rates

Figure 7.12: Average heating rate of water for varying primary airflow rates

Figure 7.12 represents the average heating rate for various primary airflow rates. The data suggest that this measure is positively correlated with the primary airflow rate. Therefore the introduction of a primary air fan may shorten boiling time.
CHAPTER 7. EFFECT OF PRIMARY AIRFLOW

7.5 Temperature control

An extension goal set-out in Section 3.1.2 related to the development of a device to control heat output from a TLUD stove. The device proposed to control heat output by throttling primary airflow. However, it is clear that throttling primary airflow below natural draft worsens stove performance, and has little impact on the maximum temperature observed within the chimney. Therefore it is highly likely that such a device would be ineffective, and detrimental to stove performance. Consequently, the development of such a device was not pursued.

7.6 Summary

The findings for primary airflow rate testing are summarised in Table 7.1. The data suggest that primary airflow should not be throttled for a stove that entrains air naturally at the primary air inlet. On balance, the data suggest that the incorpora-
tion of a primary air fan into TLUD stove designs has little positive effect on stove performance when compared to the natural draft baseline.
CHAPTER 7. EFFECT OF PRIMARY AIRFLOW

Emissions

- The average natural draft primary airflow rate for the testing stove was within the range of 110 - 120 L/min;
- airflow above natural draft reduced the length of the initial phase, and resulted in lower normalized CO peaks in this phase relative to natural draft;
- increasing the airflow rate above natural draft had little effect on combustion efficiency in the steady-state phase;
- normalized NO$_X$ emissions in the steady-state phase increased, and then plateaued as the primary airflow rate increased;
- normalized CO emissions in the final phase increased with increasing airflow rates;
- throttling airflow below natural draft lead to increased normalized CO emissions in the final and steady-state phases.

Temperature

- The minimum temperature of pre-combusted volatiles was positively correlated with the primary airflow rate;
- the maximum temperature observed within the chimney increased, and then plateaued for primary airflow rates above natural draft.

Heat Transfer

- The heating rate was positively correlated with the primary airflow rate;
- throttling primary airflow below natural reduced heat transfer to water in a pot;
- natural draft airflow resulted in greater heat transfer to water in a pot than all controlled primary airflows tested.

Table 7.1: Effect of primary air - key findings
Chapter 8

Effect of Secondary Airflow

The effect that secondary airflow had on TLUD stove performance was examined. The analysis suggests that increasing secondary airflow above natural draft reduces normalized CO emissions in the initial and steady-state phases of combustion. Marginal reductions in normalized CO were observed in the final phase as the airflow rate increased above natural draft. Other emissions, such as H$_2$ and NO$_X$ were shown to decrease significantly as the secondary airflow rate increased. The reduction in emissions observed suggests that the incorporation of secondary airflow fans can have a significant positive impact on the performance of TLUD stoves.

8.1 Stove configuration

Both the primary and secondary airflow rates are controlled. For each test the primary airflow rate is kept constant at 118 L/min. Details of the stove configuration are contained in Appendix F.
8.2 Methodology

Secondary airflow supplied to the stove was varied, and emissions and temperature data recorded. For all tests, the primary airflow rate was kept constant at 118 L/min - a rate that was shown in Section 7.2 to approximate the average natural draft primary airflow rate.

Secondary airflow testing bounds were determined by observing that the secondary airflow rate was negatively correlated with normalized CO emissions in the steady-state phase. Controlled secondary airflows that resulted in normalized CO systematically above and below the natural draft case were taken as bounds. Two intermediate and equally spaced flow rates were then selected within these bounds. Three repeat tests were conducted at each airflow rate, and the data was then processed using the method outlined in Section 6.3.1. Data obtained from this range gave an insight into the effect of both decreasing and increasing secondary airflow relative to natural draft. Measures for emissions, temperature, and heat transfer are plotted against airflow, which allowed relationships between these measures and secondary airflow to be observed.

8.3 Testing range

It is expected that as secondary airflow is throttled, less oxygen will interact with the volatiles produced within the testing stove, resulting in a higher incidence of incomplete combustion. Therefore products of incomplete combustion, such as CO, are expected to be negatively correlated with the secondary airflow rate. This expected negative correlation was used to construct a testing range. Figure 8.1 represents normalized CO emissions evolved in the steady-state phase of combustion, with the dashed horizontal line representing the equivalent measure for the natural draft.
CHAPTER 8. EFFECT OF SECONDARY AIRFLOW

Figure 8.1: Mean normalized CO in steady-state phase for varying secondary airflow rates

case. The trend in this figure is consistent with the behaviour expected from first principles, i.e. increasing secondary airflow decreases normalized CO emissions.

Two airflow rates, 328 L/min and 574 L/min, resulted in normalized CO emissions which were systematically above and below the normalized CO emissions observed under natural draft. This suggested that the average natural draft secondary airflow rate resided within these bounds. Two equally spaced intermediate airflows, being 410 and 492 L/min respectively, were selected within these bounds. These bounds, and the intermediate flow rates constitute the testing range for secondary airflow.
8.4 Results

The data suggest that increasing the secondary airflow rate led to significant reductions in normalized CO emissions during the initial and steady-state phases of combustion. Less significant reductions in normalized CO emissions were observed in the final phase. Water Boiling Tests (WBTs) reveal that the average heating rate, as well as the heat transferred to water in a pot is relatively insensitive to changes in the secondary airflow rate.

8.5 Error analysis

The flow meter used for secondary air testing was rated as being accurate to ±0.4% of the maximum value flow - which for the float used was 820 L/min. However, for the same reasons outlined in Section 7.4.1, the float fluctuated about the targeted value over the course of each test. An error of ±2% of the maximum value was deemed sufficient to take into account these fluctuations. Therefore error of ±16 L/min was associated with each secondary airflow rate tested.

8.5.1 Emissions

Figures 8.2a and b represent the normalized peak CO and H$_2$ emissions evolved in the initial phase. The figure shows large reductions in the magnitudes of these peak relative to natural draft. The constant rate at which secondary air is supplied to the stove may be the reason for this difference.

In a natural draft configuration, when the stove was first lit combustion occurred predominantly at the fuel stack, and oxygen that resided within the stove body was consumed. Little secondary air was entrained in this initial phase. When
CHAPTER 8. EFFECT OF SECONDARY AIRFLOW

conducting secondary air testing a constant rate of secondary airflow was supplied to the stove over all stages of the combustion cycle. Consequently, a greater amount of oxygen was supplied in the initial phase than what would occur under natural draft. This resulted in more complete combustion in the initial phase, and lowered the magnitude of initial normalized CO and \( \text{H}_2 \) peaks.

Figure 8.1 represents the mean normalized CO emissions in the steady-state phase of combustion. The dashed horizontal line represents the equivalent measure when the primary airflow was controlled at 118 L/min and secondary airflow was entrained naturally. The dashed horizontal line, representing the natural draft case, intersects the line connecting the data points at approximately 400 L/min - suggesting that average secondary airflow under natural draft is close to this rate.

Increasing airflow above 400 L/min significantly decreased the normalized CO emissions evolved, with an increase from 410 L/min to 492 L/min halving the normalized CO emissions observed. Only marginal reductions were realised for further increases above 492 L/min.

The data suggest that incorporating a secondary air fan has a positive effect on reducing harmful emissions. However, the data also suggest there is a limit to which higher airflow rates are able to improve stove performance. This result can assist in the of sizing secondary air fans. The analysis suggests that large fans capable of delivering high airflow rates may be no more effective at reducing emissions than smaller, cheaper fans.

Figure 8.3 represents the mean normalized CO emissions in the final phase of combustion. From the figure, increasing the airflow rate above natural draft had little effect on normalized CO emissions in the final phase. In the final phase fuel was predominantly combusted at the fuel stack, which was beneath the secondary air inlet. Therefore increasing the secondary airflow rate had little impact on CO emissions evolved, as combustion had occurred prior to the introduction of additional
CHAPTER 8. EFFECT OF SECONDARY AIRFLOW

There appeared to be no relationship between NO\(_X\) emissions and the secondary airflow rate in the final phase of combustion as shown in Figure 8.4. However, it was observed that NO\(_X\) emissions were systematically lower for all airflow rates tested than the natural draft case. Controlled secondary air may be inhibiting the formation of NO\(_X\) by cooling evolved gases, thereby reducing the rate at which reactions occur between O\(_2\) and NO\(_2\) in the atmosphere to form NO\(_X\).

8.5.2 Temperatures

Figure 8.5 represents the maximum temperature observed within the chimney for various secondary airflow rates. The figure suggests that this measure was not systematically related to the secondary airflow rate. Therefore devices that attempt to control stove temperature are unlikely to be effective if the targeted parameter is the secondary airflow rate.

The natural draft chimney temperature has not been plotted in Figure 8.5. Due to...
CHAPTER 8. EFFECT OF SECONDARY AIRFLOW

Figure 8.3: Mean normalized CO in final phase for varying secondary airflow rates

Figure 8.4: Mean normalized NO\textsubscript{X} in final phase for varying secondary airflow rates
unforeseeable circumstances it was not possible to use the same thermocouple for all tests conducted throughout the current project. Different thermocouples were used for natural draft, and controlled secondary air testing. The thermocouples resulted in very different chimney temperature measurements, with differences as large as 200°C observed during the steady-state phase. Therefore it was not instructive to plot the natural draft baseline on Figure 8.5.

### 8.5.3 Water boiling tests

The relationship between secondary airflow and heat transfer is shown in Figure 8.6. Providing constant secondary airflow led to a significant increase in heat transfer relative to natural draft - up to 27%. However, the heat transfer was relatively insensitive to secondary airflow over the range tested. A similar insensitivity was observed for the average heating rate, shown in Figure 8.7. These figures suggest that introducing forced secondary air can greatly improve heat transfer to a pot.
Figure 8.6: Heat transfer to water and pot for varying secondary airflow rates

Figure 8.7: Average heating rate of water for varying secondary airflow rates

However, high airflow rates are not met with a corresponding increase in performance - suggesting that bigger is not necessarily better with respect to fan sizing.
The testing stove’s average natural draft secondary airflow rate was approximately 400 L/min;
- controlled secondary airflow reduced normalized CO and H$_2$ in the initial phase for all airflows tested;
- increasing the airflow rate above natural draft significantly reduced normalized CO emissions in steady-state;
- normalized CO emissions in the final phase were approximately constant for increasing airflow rates;
- throttling airflow below natural draft led to increased normalized CO emissions in the steady-state phase.

The maximum temperature observed within the chimney was insensitive to changes in secondary airflow.

Controlled secondary airflow significantly increased the heat-transfer to water, relative to natural draft;
- heat transferred to water was invariant to changes in secondary airflow;
- the heating rate of water was invariant to changes in secondary airflow.

### Table 8.1: Effect of secondary air - key findings

| Emissions | • The testing stove’s average natural draft secondary airflow rate was approximately 400 L/min; |
| Temperature | • The maximum temperature observed within the chimney was insensitive to changes in secondary airflow. |
| Heat Transfer | • Controlled secondary airflow significantly increased the heat-transfer to water, relative to natural draft; |
| | • heat transferred to water was invariant to changes in secondary airflow; |
| | • the heating rate of water was invariant to changes in secondary airflow. |

8.6 Summary

A summary of the key findings from secondary air testing is presented in Table 8.1. On balance, the data suggest that the incorporation of secondary air fans are likely to be beneficial in with respect to reducing harmful emissions, and heat-transfer to the contents of a pot.
Chapter 9

Effect of Fuel Size

The effect that fuel size had on stove performance was investigated. Different fuel sizes were made by moulding cow dung into different sized discs, and were then combusted in the testing stove. It was observed that increasing the disc size resulted in greater normalized CO emissions, lower average heating rates, and reduced heat transfer to a pot. The analysis suggests that TLUD stoves are best suited to combusting small pieces of fuel with high surface area to volume ratios.

9.1 Stove configuration

The primary airflow rate was controlled at 118 L/min, and the secondary air was entrained naturally through openings in the chimney. Further details of the stove configuration can be found in Appendix H.
9.2 Methodology

Cow dung was used to investigate the effect fuel size had on stove performance. Dung was selected because it can be formed into different shapes with relative ease, and is also a representative type of biomass burned in many countries. A standardised method for dung-fuel preparation was developed, the details of which can be found in Appendix C.2. The procedure was used to shape dung into discs with diameters 45 mm, 60 mm, and 80 mm respectively. The 80 mm discs were 20 mm thick, while the 45 mm and 60 mm discs were 15 mm thick. A internationally recognised standard to control the moisture content of dung does not exist. In lieu of a specific standard for dung, a standard used to control the moisture content of wood samples for combustion was adopted (ASTM, 2003).

The primary airflow rate and the fuel size were correlated. As the size of fuel increases, so too did the gaps between pieces - imposing less restriction on primary airflow, resulting in higher flow rates. This endogeneity was addressed by controlling the primary airflow rate at 118 L/min - a rate which approximates natural draft primary airflow as found from Section 7.2.1. The different sized discs, each with different surface area to volume ratios (SAVRs) were combusted in the stove. Emissions and temperature data obtained were analysed using the procedure outlined in Section 6.3. Measures obtained from each fuel size were plotted against the SAVR, which allowed relationships between a fuel’s SAVR and stove performance to be determined.

9.3 Results

The data suggest that a fuel’s SAVR can have a significant impact on the effective operation of a TLUD stove. Large fuel pieces, with low SAVRs, did not result
in combustion occurring at the secondary air inlet - preventing the testing stove from operating as a TLUD stove. Emissions and temperature data collected suggest that a critical SAVR may exist, below which a TLUD stove may cease to operate effectively.

9.3.1 Error analysis

Errors for the airflow rates were calculated in the same way as described in Section 7.4.1. The error for the SAVR was calculated by assuming the diameter of the disc can vary by 10 mm. Details of the calculations can be found in Appendix H.2.

9.3.2 Emissions results

Normalized CO emissions traces were significantly affected by a fuel’s SAVR. Figure 9.1 shows how normalized CO traces for the 45 mm and 60 mm diameter discs, having SAVRS of 0.22 and 0.19 respectively, exhibit characteristics which are consistent with TLUD stove operation. These traces show an initial peak, followed by a steady-state phase of low emissions, finishing with a peak in the final stages of combustion. These features were not observed for the 80 mm diameter discs as shown in Figure 9.1c. Also, no flame was observed at the secondary air inlet when combusting the 80 mm diameter discs; indicating that combustion was occurring directly at the fuel stack for the duration of the test. This suggests that large fuel pieces with low SAVRs will not efficiently combust within TLUD stoves.

Figure 9.2 shows how changes in the relative surface area affect normalized CO emissions during the steady-state phase. As the SAVR increases, mean normalized CO emissions in steady-state phase decrease. It should be noted that the data analysis procedure was modified when analysing data for the largest fuel size. The
decision rules used to separate and analyse emissions in different phases relied on features such as initial and final peaks. Figure 9.1c does not clearly exhibit any of these features. To overcome this, the steady-state phase was explicitly defined to begin 20 s after ignition and last for 330 s.

Increasing a fuel’s SAVR increases the number of potential sites from which volatile gases can escape - increasing the rate of release of volatiles. This in turn affects the rate of combustion at the secondary air inlet. If volatiles are not released at a sufficiently high rate, combustion cannot be sustained at the secondary air inlet, confining combustion to the fuel stack. This mechanism is likely to explain the differences in the observed combustion characteristics for the different sized fuels.

Figure 9.2 represents the mean normalized CO emissions observed in steady-state for varying SAVRs. The largest fuel size results in significantly higher normalized CO emissions in the steady-state phase when compared to the smaller fuel sizes tested. The data also indicates that a SAVR transition region exists. If the SAVR of a fuel is below a critical threshold, combustion will only occur directly at the fuel stack, resulting in high concentrations of normalized CO emissions. If the SAVR of a fuel is above this threshold, combustion is able to occur at the secondary air inlet, leading to a significant reduction in normalized CO emissions.

9.3.3 Temperature

Figure 9.3 represents the minimum temperature of pre-combusted volatile in steady-state for different fuel SAVRs. For SAVRs of 0.15 and 0.19 the mean minimum temperature was approximately 440 °C. A significant reduction of 80 °C (13.5%) was observed when the SAVR increased from 0.19 to 0.22. This indicates that less combustion occurred directly at the fuel stack as the SAVR increased.
Figure 9.1: Normalized CO emissions traces for varying SAVRs.

(a) Surface Area : Volume = 0.22
(b) Surface Area : Volume = 0.19
(c) Surface Area : Volume = 0.15
CHAPTER 9. EFFECT OF FUEL SIZE

Figure 9.2: Mean normalized CO emissions in steady-state phase for varying SAVRs

Figure 9.3: Mean minimum temperature of pre-combusted volatiles in the steady-state phase for varying SAVRs
9.3.4 Water boiling tests

Direct combustion at the fuel stack allowed additional time for combusted gases to cool before reaching the pot, than if combustion occurred at the secondary air inlet. This in turn had a large impact on heat transferred to water in a pot as shown in Figure 9.4, which shows the effect that fuel size has on the maximum water temperature reached during a WBT. The largest fuel size, with the lowest SAVR, resulted in a maximum temperature of only 45 °C. Comparatively, the smaller fuel sizes were capable of reaching maximum water temperatures of 80 °C.

Figure 9.5 shows the average heating rate for the three fuel sizes tested. Direct combustion at the fuel stack more than halved the average heating rate of water in a pot when compared to scenarios where combustion was observed at the secondary air inlet. Similarly, Figure 9.6 demonstrates a significant reduction in the quantity of heat transferred to water when combustion occurs directly at the fuel stack, relative to combustion occurring at the secondary air inlet.
Figure 9.5: Average heating rate of water for varying SAVRs

Figure 9.6: Heat transfer to water and pot for varying SAVRs
9.4 Summary

A summary of the key findings for fuel size testing is presented in Table 9.1. The data suggest that if a fuel’s SAVR is sufficiently low, secondary combustion may not occur, and the stove will perform poorly. Therefore fuel shapes and sizes with high SAVRs are most suitable for combustion in TLUD stoves.
CHAPTER 9. EFFECT OF FUEL SIZE

| Emissions                  | • Combustion did not occur at the secondary air inlet for the fuel with the lowest SAVR; |
|                           | • direct combustion at the fuel stack resulted in significantly higher normalized CO emissions in the steady-state phase, relative to combustion occurring at the secondary air inlet; |
|                           | • a SAVR transition region between 0.15 to 0.19 existed for the type of fuel and stove configuration used. Below this range, secondary combustion did not occur, and the testing stove did not operate as a TLUD stove. Therefore the SAVR of a fuel has can significantly affect the operation of a TLUD stove; |

| Temperature                | • Increasing the SAVR from 0.19 to 0.22 caused the minimum temperature of pre-combusted volatiles in steady-state to a drop by 13.5%. |

| Heat Transfer              | • Fuels with low SAVRs significantly reduced the heating rate of water; |
|                           | • the quantity of heat transferred to water was more than halved when combustion was unable to occur at the secondary air inlet; |
|                           | • when combustion does occur at the secondary air inlet, further increases in SAVR had little effect on the quantity of heat transferred. |

Table 9.1: Effect of fuel size - key findings
Chapter 10

Effect of Fuel Stack Location

The location at which the fuel stack resides within the stove was varied. Varying the location changed the distance between the top of the fuel stack and the secondary air inlet. These changes influenced the residence time of volatile gases within the stove prior to combustion. The data suggest that this stove parameter can play an important role with respect to TLUD stove performance. Reducing the distance between the top of the fuel stack and the secondary air inlet eliminated the initial normalized CO peaks observed from previous testing. This reduction in distance did however result in higher mean normalized CO emissions during the steady-state phase. These two competing effects suggest that an optimum fuel stack location for a given stove may exist.

10.1 Stove configuration

Primary airflow was controlled at 118 L/min, while secondary air was entrained naturally through openings in the chimney. Details of the stove configuration can be found in Appendix G.
CHAPTER 10. EFFECT OF FUEL STACK LOCATION

10.2 Methodology

The distance between the top of the stack and the centre of the secondary air inlet, known as the separation distance, was controlled by altering the location the fuel stack. The four different separation distances which constituted the testing range were: 80 mm, 170 mm, 270 mm, and 370 mm. Three repeat tests were taken for each separation distance, and the data processed using the procedure outlined in Section 6.3.1. Measures obtained for each separation distance were then plotted, allowing relationships to be observed.

10.3 Results

Initial normalized CO peaks decreased in magnitude as the top of the fuel stack was moved closer to the secondary air inlet. However, emissions reductions in the initial phase were counteracted by higher normalized CO emissions during the steady-state phase. These competing effects may suggest that an optimum fuel stack location exists for a given TLUD stove.

10.3.1 Emissions

Figure 10.1 shows the normalized CO traces arising from the four separation distances analysed. Decreasing the separation distance allowed the flame to more easily transition to the secondary air inlet. This in turn reduced the length of the initial phase, and greatly decreased the magnitude of the peak normalized CO emissions in this phase, as shown in Figure 10.3. However, this reduction in the initial phase is counteracted by an observed increase in mean normalized CO emissions during the steady-state phase. Figure 10.2 represents the mean normalized CO emissions
evolved in steady-state, and suggests that as the separation distance decreases, normalized CO emissions increase. As the fuel stack moves closer to the secondary air inlet, volatiles within the stove may have less time to mix with air prior to combusting, increasing the incidence of incomplete combustion - resulting in higher normalized CO emissions.

The steady-state burn-time was significantly lengthened when the separation distance was decreased. Figure 10.4 shows the mean time spent in the steady-state phase for each fuel stack location. The lowest separation distance had a steady-state burn-time twice that of the largest separation distance. This increase may be partly attributable to a reduction in the length of the initial phase as the separation distance decreased. Less time spent in the initial phase caused less fuel to be consumed in this phase. A greater amount of fuel could then be consumed in the steady-state phase, thereby prolonging the steady-state burn-time.

Changes in radiant heat transfer to the fuel stack may also influence the steady-state burn-time. Decreasing the separation distance caused the top the fuel stack to reside closer to the flame at the secondary air inlet. Therefore smaller separation distances resulted in more radiant heat being delivered to the fuel stack - better sustaining the rate of release of volatiles from the fuel. This may result in more energy being extracted from a fuel for a longer period during the steady-state phase.

### 10.4 Temperature

The maximum temperature within the chimney was shown to vary little as the separation distance was altered. Figure 10.5 shows the maximum chimney temperature observed for various separation distances. The change in the location of the thermocouple relative to the top of the fuel stack may explain the weak negative trend shown in the figure. Decreasing the separation distance caused the top of the fuel
CHAPTER 10. EFFECT OF FUEL STACK LOCATION

Figure 10.1: Normalized CO emissions traces for varying separation distances

Figure 10.2: Mean normalized CO emissions in steady-state phase for varying separation distances
CHAPTER 10. EFFECT OF FUEL STACK LOCATION

Figure 10.3: Mean normalized peak CO in initial phase for varying separation distances

Figure 10.4: Mean time in steady-state phase for varying separation distances
Figure 10.5: Maximum temperature within chimney for varying separation distances

stack to reside closer to the thermocouple within the chimney. A possible explanation for this is that additional radiant heat is delivered to the thermocouple from the fuel stack. As the separation distance increased, the radiant heat transferred to the thermocouple from the stack would decrease - giving rise to the weak negative relationship observed.

10.5 Summary

A summary of the key findings is presented in Table 10.1. The separation distance was shown to have a significant effect on stove performance. Therefore, the fuel stack location is a parameter that should be carefully considered when developing new TLUD stove designs.
CHAPTER 10. EFFECT OF FUEL STACK LOCATION

| Emissions                          | • Reducing the separation distance between the top of the fuel stack and the secondary air inlet eliminated initial normalized CO peaks; |
|                                   | • mean normalized CO emissions in steady-state were negatively correlated with separation distance; |
|                                   | • the above competing effects suggest it may be possible to determine an optimum separation distance. |
| Burn-time                         | • The burn-time in the steady-state phase increased significantly as the separation distance decreased. |
| Temperature                       | • A weak, negative relationship existed between the maximum temperature observed within the chimney and the separation distance. |

Table 10.1: Effect of fuel stack location - key findings
Chapter 11

Effects of Fuel Stack Depth

The depth of the fuel stack was altered, and the emissions and temperatures generated analysed. The effect that this parameter had on TLUD stove performance was inconclusive, and it is suggested that additional testing be conducted in the future.

11.1 Stove configuration

Primary air was supplied to the stove at a controlled rate of 118 L/min. Secondary air was entrained naturally through openings in the chimney. Details of the stove configuration and testing procedures can be found in Appendix I.

11.2 Methodology

The mass of fuel combusted was kept constant, allowing the determination of the sole effect that varying the fuel depth had on stove performance. Small rocks were used to alter the depth. A layer, 6 mm in depth, was placed upon the fuel grate,
with 700 g of fuel placed on-top of this layer. The stove was then operated, and emissions data collected. Comparisons were then made between stove configurations with different fuel stack depths - giving an indication as to the effect this parameter had on stove performance.

11.3 Results

Figure 11.1 compares the normalized CO traces for tests with and without rocks on the fuel grate. The blue traces were found previously when conducting primary air testing at 118 L/min, and represent the stove configuration without rocks. The single red trace represents the emissions profile generated with rocks placed on the fuel grate. It should be noted that due to time constraints only one test with rocks was conducted.

The traces in Figure 11.1 suggest that increasing the depth of the fuel stack has little influence on the general trend of the normalized CO trace. The initial peak for the test with rocks did however reside amongst the lowest of the no-rocks traces. Due to only one test being conducted it is not possible to determine if this feature is repeatable.

11.4 Summary

The results from this test are inconclusive due to limited testing; however, the general trend of the normalized CO profile for the test with rocks was very similar to the profiles generated without rocks. There may be the potential to decrease the magnitude of the initial normalized CO peak by increasing the depth of the fuel stack - further testing is required to determine this conclusively.
Figure 11.1: Normalized CO traces for varying fuel stack depths
Chapter 12

Recommendations

The project has revealed several insights into the way in which TLUD stove parameters impact stove performance. The key findings presented in Tables 7.1, 8.1, 9.1, have been used to make the following recommendations:

1. When entraining secondary air naturally, it is inadvisable to throttle primary airflow below natural draft. Doing so will decrease combustion efficiency and result in less heat transfer to a pot;

2. increasing the secondary airflow rate above natural draft increases combustion efficiency. Therefore incorporating secondary air fans into TLUD stoves is likely to have a positive effect on stove performance;

3. there is a limit to which increasing secondary airflow improves stove performance. Large, expensive fans may be no more effective at improving combustion efficiency than smaller, cheaper fans. Therefore careful consideration should be given to fan sizing when designing TLUD stoves;

4. increasing the primary airflow rate above natural draft has little effect on combustion efficiency in the steady-state phase. Combustion efficiency decreases
in the final phase for increasing primary airflow rates. Therefore greater care
should be taken to extinguish a TLUD stove at the end of the steady-state
phase if it incorporates a primary air fan;

5. if only incorporating one type of fan, it is advisable to incorporate a secondary
air fan. Secondary air fans outperform primary air fans with respect to com-
bustion efficiency in each stage of the combustion cycle;

6. combusting large fuel pieces may prevent a TLUD stove from operating ef-
effectively. It is recommended that large pieces of fuel be broken up prior to
combustion;

7. the magnitude of peak CO emissions in the initial phase can be greatly reduced
by positioning the top of the fuel stack close to the secondary air inlet;

8. it is advisable to design stoves with fuel grates that can be varied in height. An
optimum separation distance between the top of the fuel stack and the centre
of the secondary air inlet is likely to exist for a given TLUD stove. Optimising
this parameter can eliminate initial CO peaks, and prolong the burn-time in
the steady-state phase of combustion. When designing TLUD systems, time
should be devoted to finding the optimum fuel stack location. The separation
distance which optimises stove performance could be marked within a stove,
giving users a reference against which to position the top of the fuel stack.

These recommendations will hopefully assist in the construction of more efficient
TLUD stoves, as well as directing future research efforts into the optimisation of
their design.
Chapter 13

Future Work

13.1 Fuel stack depth

The extension goal of investigating the effect that fuel stack depth had on stove performance was partially completed due to time constraints. It is recommended that further work be done to develop a more complete understanding of how this parameter influences stove performance. However, the available result shown in Chapter 11 may suggest that this parameter is capable of influencing emissions evolved. Additional fuel stack depths should be tested to better understand the relationship between this parameter and stove performance.

13.2 Scalability

The current project has identified several relationships between stove parameters and stove performance. However, it is not known if these relationships will be observed in smaller TLUD systems. It is recommended that a smaller testing stove,
representative of a TLUD stove used in the field, be constructed. A similar analysis to that undertaken in the current project could be conducted. It may then be possible to identify scalable ratios, such as airflow rates or stove geometries, that optimise the performance of TLUD stoves of different sizes. End-users could then follow these design ratios to construct optimised TLUD stoves, which could be tailored to their individual heating and cooking requirements.
Chapter 14

Conclusion

The current project used a purpose built testing stove to undertake fundamental research into the combustion science of TLUD stoves. Commissioning the testing stove revealed that it was capable of operating as a TLUD stove. Particular emphasis was then placed on determining the effect that primary and secondary airflow rates had on stove performance. The analysis suggested that fans at the secondary air inlet would be more effective at reducing emissions than primary air fans. The effect fuel size had on combustion characteristics was also investigated, leading to the conclusion that smaller fuel pieces are more suited to TLUD stove operation. In addition to airflow rates and fuel size, the fuel stack location was also shown to significantly influence emissions evolved. Recommendations regarding the design and operation of TLUD stoves were then made.

Extension goals relating to raising the profile of the current project have also been accomplished. Relationships were developed between the University of Adelaide and World Vision Australia with respect to improved cookstove research. The current project was also promoted on a television program, called Scope, which will be broadcast on network television in early 2015.
In summary, the current project has contributed to the understanding of the effect that TLUD stove parameters have on stove performance. It is hoped that the recommendations developed will provide guidance for future research into TLUD stoves, and assist in the optimisation of these stoves in the field.
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Annex I

Draft Journal Article
The Effect of Primary and Secondary Airflow on Emissions for a Top-Lit Up-Draft Cookstove

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Abstract
Over 3 billion people rely on biomass fuels such as wood, dung, and agricultural residues to meet daily energy requirements for cooking and heating. These fuels are often combusted inefficiently in traditional cookstoves, leading to the evolution of harmful emissions. Severe health effects are associated with long-term exposure to these emissions, with 4 million deaths attributable to indoor air pollution (IAP) annually. Improved cookstoves, which combust biomass fuels more efficiently than traditional stoves, have been developed to address this issue. The Top-Lit Up-Draft (TLUD) cookstove is a type of improved cookstove which combuts biomass fuel in a two stage combustion process. These stoves have been shown to significantly improve combustion, and can be operated with and without fan assistance. The current study examines the effectiveness of primary and secondary air fans in TLUD stove designs. The findings suggest that increasing primary airflow above natural draft had little effect on combustion efficiency, while increasing secondary airflow led to a significant improvements in combustion efficiency.

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Keywords: Top-Lit Up-Draft, TLUD, improved cookstove, parametric analysis

1. Introduction
Currently 40% of the world’s population rely on biomass fuels such as wood, agricultural residues, and animal dung for cooking and heating purposes [1, 2]. These fuels are often combusted inefficiently using primitive technologies, leading to the evolution of high concentrations of harmful emissions known as Household Air Pollution (HAP). It is estimated that exposure to these emissions results in the deaths of approximately 4 million people annually [3]. In an effort to address this problem, improved cookstoves have been developed. These cookstoves aim to combust biomass fuels more efficiently than traditional stoves, and in doing so reduce the levels of harmful emissions evolved.

Semi-gasifier cookstoves have been promoted as a next-generation improved cookstove technology [4]. One such semi-gasifier stove is the Top-Lit Up-Draft (TLUD) stove. Several types of TLUD stoves are on the market today, and they have been disseminated in developing countries with the intent of reducing HAP. Fan assisted TLUD stove are becoming increasingly popular, however there is currently limited data supporting the effectiveness of fans in TLUD stove designs. The current study addresses this issue by using a purpose built TLUD testing stove, capable of controlling primary and secondary airflow rates. The testing stove is operated at controlled airflow rates which are
estimated to be above and below the average natural draft rate. Systematic trends are then observed to evaluate the effectiveness of devices, such as fans, in TLUD stoves.

Despite their prevalence, relatively little rigorous scientific analysis has been undertaken to optimise their design. The current project has made progress to address this issue by undertaking a parametric analysis of a TLUD stove. This analysis was accomplished by using a purpose built testing stove which enabled the independent control of several stove parameters, which were: the primary airflow rate, the secondary airflow rate, the fuel stack location, and the fuel size. Following an analysis of the data for each parameter, recommendations regarding TLUD stove design were made.

2. Apparatus

The TLUD testing stove used in the current study is shown in Figure 1. The cylindrical steel body of the stove has an internal diameter of 206 mm, and is 1.6 m tall. The chimney has three slots, each 20 mm wide, to allow the natural entrainment of secondary air. Primary air was delivered to the stove via a compressed air supply. Temperature data was collected using two sleeved K-type thermocouples at locations A and C. Gaseous emissions data for carbon dioxide (CO$_2$), carbon monoxide (CO), nitrogen oxides (NO$_X$), hydrogen (H$_2$), and oxygen (O$_2$) were collected using a Testo 350XL gas analyser. The probe of the analyser was positioned 0.83 m above the top of the chimney, with the probe in-line with the centreline of the stove.

3. Method

Prior to controlling primary and secondary airflow rates, the stove was allowed to entrain air naturally through openings in the stove body. The emissions and temperature data collected in this phase of testing were used a benchmark against which controlled airflow testing was compared.

- For each test, 700 g of Jeffries PlayScape bark chips were combusted in the testing stove.
- Mention hot-start test. Stove body at location C was 130 °C at time of ignition.

A testing range was established by The approach examined TLUD stove operation from first principles, and identified two stove metrics which are correlated with the primary airflow rate - the mean normalized CO concentration,
and the minimum temperature of pre-combusted volatiles in the steady-state phase. The primary airflow rate was varied, and the correlated metrics were compared to results obtained from natural draft testing. Controlled airflow rates resulting in metrics systematically above and below the natural draft metric were identified, and suggest that the average natural draft airflow rate resides within these airflow bounds. Two intermediate airflow rates at equally spaced intervals were selected within these bounds, and repeat tests were undertaken at each airflow rate. Measures obtained from this analysis have been plotted against the primary and secondary airflow rates, and the results are compared to the natural draft case. A determination was then made regarding the effect that varying the primary and secondary airflow had on stove performance.

• Discuss details of each test
• 700 g Jeffries PlayScape bark chips
• 10 mL methylated spirits as lighter fluid. Paper towel set alight as ignition source
• Discuss normalized procedure. Refer to Jetter et al. for reasons regarding normalization of CO/CO₂. Use references to justify why normalized CO is reasonable measure of true combustion efficiency.
• Mention how primary airflow was controlled when undertaking tests to determine the effect that secondary airflow had on stove performance.

4. Results

4.1. Effect of Primary Airflow
• Discuss general features of normalized CO traces: Initial peak, steady-state, and final peak. Refer to Figures 2. Note: this figure refers to benchmarking data - natural draft primary and secondary airflows.
• Discuss how mean value of blue (steady-state) section is taken for each test. The mean of this mean is taken for eight tests. Allows systematic differences between configurations to be observed.
• Discuss the determination of bounds. Iterative approach. Used expected correlation between normalized CO and primary airflow rate to determine bounds. Values were (78 L/min, 98 L/min, 118 L/min, 138 L/min)
  Data suggest natural draft primary airflow is in the range of 90 - 120 L/min
• Refer to Figure 1a. Increasing the airflow above 110 L/min had little effect on stove performance. Very similar to baseline level. Suggests that increasing airflow above natural draft is not particularly beneficial in steady-state.
• Refer to Figure 3a and discuss how increasing primary airflow in the final phase may cause more CO (relative to natural draft) to be released. Perhaps increasing char combustion is better sustained in the final phase with the use of a fan. (Char combustion within the stove leads to much higher normalized CO emissions).
• Increasing primary airflow rates above natural draft has little positive impact on stove performance. Note that decreasing airflow below average natural draft (when entraining secondary air naturally) flow rate mad stove performance worse (important result).

5. Effects of Secondary Airflow
• Using the same method as for primary air, a correlation between the secondary airflow rate and normalized CO emissions in steady-state was used to determine the testing bounds.
• Data suggest that average secondary airflow rate is approximately 400 L/min.
Figure 1: Effect of primary airflow in different combustion phases

(a) Mean normalized CO emissions in steady-state phase
(b) Mean normalized CO in final phase

Figure 2: Features of normalized CO traces
• Increasing secondary airflow above natural significantly reduces normalized CO emissions in the initial phase. May be due to higher airflow in the initial phase than what would occur under natural draft.

• Significant normalized CO reductions observed as secondary airflow rate is increased above natural draft (above 400 L/min).

• Weak, negative correlation between secondary airflow rate and normalized CO emissions in the final phase of combustion

• Throttling secondary airflow decreases combustion efficiency (important result).

6. Conclusion

• Summarise results

• Increasing primary airflow above natural draft had little positive effect on combustion efficiency. Modest improvement in initial phase. Marginal impact in steady-state phase. Higher normalized CO emissions in the final phase.
• Increasing secondary airflow had a positive impact on all stages of combustion. Lower normalized peak magnitudes for CO emissions. Significant decrease in normalized CO emissions in steady-state phase when increasing airflow above natural draft. Lower normalized CO emissions in final phase when secondary airflow was above natural draft.

• Based on the analysis in this study, secondary air fans are more beneficial in terms of improving combustion efficiency in TLUD stoves.

References


Annex II

Promoting the TLUD Cookstove

II.1 World Vision Australia

The CEO of World Vision Australia, Tim Costello, was contacted by members of the current project group. The relevance of the research being undertaken into improved cookstoves was communicated, and a meeting was arranged. On 14 July 2014 Mr Costello visited the Thebarton Research Laboratory, where members of the group gave an overview of the current project. Preliminary discussions are currently underway which may see World Vision Australia contributing towards an ARC linkage grant for future improved cookstove research at the University of Adelaide.

II.2 Media

The current project will be featured on a science show, called Scope, to be broadcast on network television. During filming the importance of improved cookstoves was emphasised, as well as the benefits associated with TLUD stoves.
ANNEX II. PROMOTING THE TLUD COOKSTOVE

Figure II.1: Meeting with Tim Costello, CEO of World Vision Australia

Figure II.2: Channel TEN program - Scope filming
Appendix A

Testing Apparatus
A.1 Testing stove dimensions

This testing stove consists of a large cylindrical steel body 600 mm in length positioned on top of a steel primary air inlet chamber. The cylinder body has an internal diameter of 206 mm, and thickness of 7.85 mm. The primary air inlet chamber has dimensions of 248 mm x 248 mm x 150 mm (length x width x height).

Twelve tubes each 295 mm in length with an internal diameter of 10 mm protrude from the stove. These tubes enable secondary air to be delivered to the stove at a controlled rate from a compressed air supply.

![Diagram of testing stove dimensions](image)

Figure A.1: Basic dimensions of testing stove

The design of the fuel grate is such that fuel to be loaded into the stove is placed on a steel grate of thickness 1 mm. This grate is perforated with holes that allow air to pass through the grate and into the fuel stack. Each hole is 3 mm in diameter, and the ratio of hole-area to total fuel grate area is 0.26. The grate is held in place by
three stainless steel connecting rods. These rods hang over the top of the stove and allow the fuel grate to be removed and cleaned after conducting experiments. The length of the connecting rods can be altered to change the location of the fuel grate within the stove. Bolts protruding into the stove from the stove body constrain the maximum depth to which the fuel grate can be lowered to 520 mm below the top surface of the stove body.

A.1.1 Primary air set-up

Figure A.3 shows the set-up for the fitting that facilitated the supply of compressed air to the primary air inlet. The front plate was threaded, and the fitting was screwed into the plate. A $\frac{1}{2}$ inch BSP quick connect gas fitting was used. Flexible gas tubing connected this fitting to the base of the flow meter previously described.
Initially when the primary compressed air fitting was installed, swirling air currents were observed within the stove. This was due to air entering the stove through a localised position within the primary air chamber. It should be noted that these swirling currents were not observed when undertaking natural draft testing. The currents induced by the fitting altered the mixing characteristics of gases within the stove, which had the potential to affect the amount of complete combustion occurring. This would in turn influence the concentration of hazardous emissions evolved. In order to better emulate the entrainment of air under natural draft, a diffuser was designed to more evenly distribute air into the primary air chamber, thereby reducing the severity of these swirling currents.

To prevent swirling air currents within the stove, a primary air diffuser was designed and built. The diffuser was constructed by bending a 250 mm length of copper tubing into a rounded shape. The internal diameter of the tubing is 11 mm. A total of ten 2 mm holes are drilled into the pipe. Each hole is separated by a distance of approximately 20 mm. The end of the curved section of the tubing is fitted with a copper capillary cap. A connecting piece attaches to the diffuser via a press fit. The connecting piece can be screwed onto the compressed air fitting, thereby connecting the diffuser to the front plate of the primary air chamber as shown in Figure A.3.
The diffuser was installed pointing downwards, towards the base of the primary air chamber. This reduces the swirling and velocity of the air by more evenly distributing it within the primary air chamber before it moves into the stove. This in turn better replicates natural draft airflow velocities. In addition to reducing air velocity, the diffuser also has the advantage of distributing air into the primary air chamber more evenly than a fan or a single fitting. Therefore modifications to the primary air supply allows natural draft primary airflow rates to be better represented by the testing stove.

A.2 Secondary air set-up

A compressed air supply delivered a controllable amount of secondary air to the inherited testing stove. The compressed air supply connected directly to a manifold with twelve outlets that fed into the 12 tubes shown protruding from the top of the stove in Figure A.1. There were however limitations with this set up. For instance, the inherited design had no capacity to entrain secondary air into the stove under natural draft.

Initial attempts at natural draft secondary air testing involved removing the pipes shown protruding from the stove in Figure A.1. It was hoped that air would be drawn in through the holes that were left. However these holes were too small to allow sufficient airflow to enable combustion to occur at the location of these holes, instead the flame front was observed to jump to the top of the chimney. This is undesirable, as the purpose of the chimney is to ensure that a large proportion of the volatile gases undergo complete combustion within the chimney before being vented to the atmosphere. In order address this issue a new chimney was designed that would that would allow secondary air to be entrained into the stove under natural draft.
Following natural draft testing, controlled secondary air testing was pursued. This phase of testing revealed a major design flaw associated with the way in which secondary air was delivered to the stove. The problem again stemmed from the size of the holes through which secondary air was supplied. The inherited design delivered secondary air to the stove through 12 pipes, each 10 mm in diameter as can be seen in Figure A.1. The small size of the holes led to air entering the stove body through each hole at relatively high velocities. The jets emanating from these holes impinged within the centre of the stove, causing swirling currents within the stove. This is undesirable as it does not accurately reflect the way air is entrained under natural draft. To address these swirling air currents a new chimney was constructed. The chimney acts to slow down and distribute the air more evenly. This chimney had the effect of reducing the swirling effect that was observed with the inherited design.

A.2.1 Chimney used for natural secondary air testing

The inherited testing stove initially had no capacity to entrain secondary air under natural draft. Initial attempts to induce natural secondary airflows by removing the tubes which supplied controlled secondary air to the stove failed. When these tubes were removed it was observed that not enough air could be entrained through the remaining small holes to allow combustion to occur at the location of these holes. To overcome this, these holes were blocked once again and a new chimney was built. A stainless steel heater flue was used to create the stove’s chimney. The chimney has an internal diameter of 208 mm, and is made of 1 mm thick stainless steel. The chimney used for natural secondary air entrainment testing is shown in Figure A.4. Three equi-spaced 20 mm high slots were cut into the chimney to provide a location at which secondary air can be entrained into the stove. At a distance of 90 mm above the centre of the secondary air slots a 3 mm hole is drilled into the chimney.
This hole allows the insertion of a sleeved K-type thermocouple to measure the temperature within the chimney.

The chimney height is defined as the vertical distance between the centre of the secondary air inlet and the top of the chimney. Previous research by Birzer et al. (2013) has shown that the optimum chimney height is approximately 1.5 times the diameter of the stove. The internal diameter of the stove is 206 mm; therefore the optimum chimney height is approximately 309 mm. The actual chimney height is 285 mm, which is marginally shorter than the target height. However it should be noted that the target height is based on an approximation, therefore this small discrepancy is unlikely to have a significant impact on stove performance.

Figure A.4: Basic Dimensions of chimney used for natural draft testing

**Stove-chimney interface**

The internal diameter of the sourced flue for the chimney is 2 mm greater than the internal diameter of the stove. To fit the chimney within the stove three thin equi-spaced 30 mm high slits were cut into the base of the chimney. These slits allow the
Figure A.5: The base of the natural draft chimney, showing the slits cut to allow the chimney to fit inside the stove.

base of the chimney to be deformed as it enters the stove. When correctly fitted, this creates a seal between the chimney and stove. The base of the chimney sits approximately 10 mm within the stove. Figure A.5 also shows how the slits provide space for the fuel grate connecting rods to exit the stove. This prevents the rods from creating a gap between the chimney and stove body, through which air could be entrained. Aluminium foil is then used as a filler to block any gaps between the connecting rods and the slits.
A.2.2 Chimney used for controlled secondary air testing

Problems associated with the way in which the inherited design supplied controlled secondary air to the stove were discovered. The inherited design fed secondary air into the stove through twelve tubes each 10 mm in diameter. The relatively small size of these holes resulted in secondary air being delivered to the stove at high velocities. The high velocity jets emanating from each hole impinged on each other, and resulted in swirling air currents being induced within the stove. These impinging jets also pushed some of the secondary air further down into the stove body. As a consequence the inherited secondary air delivery mechanism did not accurately represent the way air would be entrained under natural draft. In order to address this issue a new controlled secondary air delivery mechanism was developed.

The design of the natural draft chimney as shown in Section A.2.1 informed the development a new delivery mechanism for controlled secondary air to the testing stove. The new mechanism involved the design and manufacture of a diffuser system. The diffuser system is made up of five components as shown in Appendix K. The base component is a chimney of the same design and dimensions as the natural draft chimney shown in Figure A.4. Around the chimney a sealed enclosure encapsulates the secondary air slots. A diffuser ring resides in between the enclosure and the slots. Controlled secondary air entering the stove is evenly distributed within the enclosure by the diffuser ring, and its velocity slowed before entering the stove body. This new delivery mechanism better emulates natural draft airflows when compared to the inherited design.

The diffuser itself was built by the Mechanical Workshop at The University of Adelaide and was built according to the drawings shown in Appendix K.

This diffuser uses four of the pipes from the same manifold that the original secondary controlled air system used. The other eight pipes contain ball valves that
can be closed to ensure no leakage during operation. The four pipes connect to the diffuser box via quick connect fittings that allow the diffuser to be easily removed from the stove, as this needs to occur between every test. The male quick connect fittings are screwed into brass pieces held within the diffuser box, which in turn connect to one internal ring. This ring has small holes drilled into at location that direct the air into the diffuser box and away from the stove. This allows the air to lose any velocity it might have and fill the box before entering the stove, which makes the controlled secondary air act more like the natural conditions required.

Figure A.6: Basic dimensions of chimney used for forced air testing
A.3 Measurement apparatus

A.3.1 Gas analyser

The gases evolved from the testing stove are analysed using the Testo 350XL gas analyser. This gas analyser is capable of measuring the concentration of several gaseous emissions emanating from the stove over time.

The gas analyser consists of a sampling probe and a control unit. A pump in the control unit draws gas into the sampling probe, and is drawn to the main body of the control unit where it is analysed. The control unit can be connected to a computer where the results of this analysis are displayed and recorded over time.

The Global Alliance for Clean Cookstoves (GACC) gives recommendations for the location of sampling probes for emissions measurements. The testing guidelines recommend that if the stove is placed under a hood extractor, as is the case for this project, that the gases be sampled in the duct immediately after the hood. This would require a hole in the duct, and was considered an inappropriate modification to the duct design. In order to overcome this, the sampling probe has been positioned within the extractor hood, close to the duct opening.

In order to control for varying dilution effects that would result as a consequence of the total height of the stove changing, the location of the probe is determined relative to the chimney. The probe is placed at a height of 840 mm above the top of the stove chimney or height of 1180 mm above the top of the stove body as seen in Figure A.7. The tip of the sampling probe is placed over the centreline of the stove body. The use of the chimney as a reference height attempts to account for dilution. As the distance between the point at which the flame exits the stove and the sampling probe location increases, so too will the dilution of the sampled emissions with air. Therefore a fixed distance between the top of the chimney and
the sampling probe is taken to attempt to control for this effect.

From visual inspection, the current sampling probe height also ensures that the probe is located above the body of the flame. Sampling above the flame better represents the emissions resulting from the stove’s operation. If sampling within the flame, the combustion process of volatiles is only partially completed, and does not provide an accurate representation of the emissions evolved from the testing stove when it is in operation.

A.3.2 Thermocouples

The mean gas temperature inside the stove and the mean exhaust temperature are measured using 3.5 mm sheathed K-type thermocouples. The relative positions of the thermocouple locations are shown in Figure A.8 with the tip of the thermocouple placed in the centre of the stove.

For tests conducted without a chimney, the thermocouple is placed at a height of 110 mm above the top rim of the steel stove body. For tests with a chimney the thermocouple location is 90 mm above the centre of the secondary air opening.

Thermocouple location A as shown in Figure A.8 measures the exhaust temperature at a fixed height of 90 mm above the secondary air inlet. The temperature of the flame will vary as the distance from the secondary air inlet changes.

Thermocouple locations B and C provide two measurement locations at which the inside stove gas temperature can be determined. The vertical separation distance between these two locations is 105 mm.

A.3.3 Flow meters and floats
Figure A.7: Testo probe location within extractor hood directly above cookstove
Figure A.8: The available thermocouple locations
## APPENDIX A. TESTING APPARATUS

### Table A.1: Flow meters and floats

<table>
<thead>
<tr>
<th>Flow Meters</th>
<th>Float</th>
<th>Airflow [L/min]</th>
<th>Pressure [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>Primary Air</td>
<td>$\frac{1}{2}$-17-G-$\frac{10}{83}$</td>
<td>$\frac{1}{2}$-GSVT-44 t60</td>
<td>19</td>
</tr>
<tr>
<td>Secondary Air</td>
<td>$\frac{3}{4}$-27-G-$\frac{10}{83}$</td>
<td>$\frac{3}{4}$-27-GSVGT-54</td>
<td>82</td>
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</table>
Appendix B

Commissioning & Preliminary Testing

B.1 Stove configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary-inlet</td>
<td>Primary air inlet enclosure panels removed</td>
</tr>
<tr>
<td>Secondary-inlet</td>
<td>Shut-off</td>
</tr>
<tr>
<td>Fuel Grate</td>
<td>520 mm from top of stove body</td>
</tr>
<tr>
<td>Chimney</td>
<td>Natural Draft Chimney</td>
</tr>
<tr>
<td>Type of bark chips used</td>
<td>Tatura, Jeffries and Radiata Pine</td>
</tr>
<tr>
<td>Location of Testo</td>
<td>1.18 m above stove centreline</td>
</tr>
<tr>
<td>Location of thermocouples</td>
<td>One thermocouple is inserted into thermocouple location A as shown in Figure A.4, and another thermocouple is inserted into thermocouple location B as shown in Figure A.1.</td>
</tr>
</tbody>
</table>
Figure B.1: Stove configuration used to commission stove
B.2 Testing procedures

1. Examine fuel grate inside stove with a torch. Clean grate if required. Check to see that fuel grate is hanging level.

2. Place a table approximately 1.5 m from the testing stove.

3. Place laptop on table.

4. Place Testo on table, and attach relevant cables and tubes.

5. Position the tip of the Testo’s sampling probe 1.18 m above the top of the cast iron stove body. Ensure sampling probe is over the centre of the stove body.

6. Connect Testo to laptop.

7. Connect thermocouples to computer.

8. Start Testo software.

9. Start thermocouple software.

10. Turn on air extraction system.

11. Check that the extractor hood is set to the ‘open’ position, and that it is free of from any obstructions.

12. Weigh desired amount of bark chips in a bucket.

13. CAUTION: When conducting the following steps avoid contact with the hot stove.

14. Pour weighed bark chips into the stove.

15. Use a torch to see if fuel is level; if not, level the fuel with a metal ruler.
16. Attach Natural Draft Chimney to top of stove body as seen in Figure B.1.

17. Roll up a piece of paper towel (approximately 190 mm x 100 mm).

18. Use an infra-red thermometer to measure the stove body temperature (SBT). The location at which this measurement is taken is shown in Figure A.1

19. Monitor the SBT. When the SBT cools to 135 °C start recording Testo and thermocouple data with their respective data acquisition softwares.

20. Pour 1 cap of methylated spirits into the stove. Aim to spread the lighter fluid as evenly as possible over the fuel.

21. Re-measure and record the SBT.

22. Light the paper towel prepared in step 15, and drop it into the stove.

23. Monitor the initial flame. If a plume of gas emanates from the stove manually light the plume with an extended lighter.

24. Photograph the flame during the gasification stage of the stove’s operation.

25. (Optional) Take a spot test of the gases within the stove. Place Testo into the Thermocouple Location B hole shown in Figure A.1.

26. Cease recording data when all relevant combustion phases are observed. (A useful indicator is the CO measurement reading from the Testo. As this value falls at the end of the combustion cycle prepare to stop recording. At 50 ppm CO stop recording thermocouple and Testo data).

27. Remove fuel grate from stove. Clean the grate with a wire brush and dispose of ash/charcoal in a bin. Place the fuel grate back into the stove.

28. Repeat steps 12 – 27 for each experiment.
Appendix C

Fuel Preparation

C.1 Bark chip preparation procedure

The moisture content of bark chips is reduced prior to combustion. This is done by placing 60 L of bark chips on perforated metal trays. Each tray has dimensions 1.70 m x 0.49 m x 0.03 m. The depth of the bark chips in the tray is approximately 0.03 m. They trays loaded with bark chips as shown Figure C.1
The trays are placed inside a drying enclosure. Air within the enclosure is heated by an air conditioning unit to approximately 37 °C. Heat is prevented from escaping the enclosure by tarpaulin. The bark chips are allowed to dry for approximately 24 hrs in the heated enclosure. Figure C.2a shows the heating set-up with the trays loaded into the enclosure, and Figure C.2b shows the sealed heating enclosure.
C.2 Dung preparation procedure

1. Shovel desired amount of dung into a container such as a bucket.

2. If dung is wet and malleable skip to step 10. If the dung is too dry and not malleable add water.

3. Soak dry dung in water and break into smaller pieces with hands, add more water if necessary.

4. Repeat step 3 until dung is wet and too small to easily break.

5. Use stick blender to turn dung clumps into a pulp like mixture.

6. Place small amounts of dung pulp into colander and squeeze out water.

7. Place slightly drier dung pulp into centre of muslin sheet. Wrap drier dung pulp in the sheet and squeeze out more water with hands.

8. Place dried out dung pulp into bucket for forming.

9. Repeat steps 6-8 until no more wet dung pulp is left.

10. Select the PVC pipe according to desired dung size and hold firmly against a horizontal flat ramming surface.

11. Place desired volume of dung into the top of the PVC pipe.

12. Use appropriately sized wooden ramming rod to ram dung inside the PVC, repeat ramming until satisfied that the dung will hold shape.

13. Lift the PVC pipe a small amount and gently force the dung out with the selected ramming rod.
14. Place shaped dung onto drying rack for further drying.

15. Repeat steps 10-14 until desired volume of dung has been shaped.

16. Place drying racks onto desired drying location and place appropriate fans to blow air onto the drying racks.

17. Turn on fans and check on shaped dung until dung is dry to touch and light in weight.

18. Turn off fans and place dried shaped dung into drying trays for oven drying.

19. Place drying trays into drying oven.

20. Seal drying oven and heat at 95 °C overnight.

21. Collect dried shaped dung from drying trays and store appropriately until required for testing.
Figure C.3: Dung preparation equipment
C.3 Moisture content determination

The moisture content of all fuels was determined by placing a small mass approximately 50 g of each batch into a pre-weighed tin. This mass was accurately measured to 2 decimals places. The tin was then placed into an oven at 95 °C overnight. The final mass was accurately weighed. The following equation was used to calculate the Moisture Content (%).

C.3.1 Moisture content determination equation

\[
\text{Moisture Content (\%)} = \frac{\text{Initial Mass} - \text{Final Mass}}{\text{Final Mass} - \text{Mass of Tin}} \times 100 \quad \text{(C.3.1)}
\]
### Appendix D

#### Natural Draft Testing

#### D.1 Stove configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary-inlet</td>
<td>Primary air inlet enclosure panels removed</td>
</tr>
<tr>
<td>Secondary-inlet</td>
<td>Shut-off</td>
</tr>
<tr>
<td>Fuel Grate</td>
<td>520 mm from top of stove body</td>
</tr>
<tr>
<td>Chimney</td>
<td>Natural Draft Chimney</td>
</tr>
<tr>
<td>Type of bark chips used</td>
<td>Jefferies Pine</td>
</tr>
<tr>
<td>Location of Testo</td>
<td>1.18 m above stove centreline</td>
</tr>
<tr>
<td>Location of thermocouples</td>
<td>One thermocouple is inserted into thermocouple location A as shown in Figure A.4, and another thermocouple is inserted into thermocouple location B as shown in Figure A.1.</td>
</tr>
</tbody>
</table>
Figure D.1: Stove configuration used for natural draft testing
D.2 Testing procedures

1. Examine fuel grate inside stove with a torch. Clean grate if required. Check to see that fuel grate is hanging level.

2. Place a table approximately 1.5 m from the testing stove.

3. Place laptop on table.

4. Place Testo on table, and attach relevant cables and tubes.

5. Position the tip of the Testo’s sampling probe 1.18 m above the top of the cast iron stove body. Ensure sampling probe is over the centre of the stove body.

6. Connect Testo to laptop.

7. Connect thermocouples to computer.

8. Start Testo software.

9. Start thermocouple software.

10. Turn on air extraction system.

11. Check that the extractor hood is set to the ‘open’ position, and that it is free of any obstructions.

12. Weigh 700 g of bark chips in a bucket.

13. CAUTION: When conducting the following steps avoid contact with the hot stove.

14. Pour weighed bark chips into the stove.

15. Use a torch to see if fuel is level; if not, level the fuel with a metal ruler.
16. Attach Natural Draft Chimney to top of stove body as seen in Figure B.1.

17. Roll up a piece of paper towel (approximately 190 mm x 10 mm).

18. Use an infra-red thermometer to measure the stove body temperature (SBT). The location at which this measurement is taken is shown in Figure A.1.

19. Monitor the SBT. When the SBT cools to 135 °C start recording Testo and thermocouple data with their respective data acquisition softwares.

20. Pour 1 cap of methylated spirits into the stove. Aim to spread the lighter fluid as evenly as possible over the fuel.

21. Re-measure and record the SBT.

22. Light the paper towel prepared in step 15, and drop it into the stove.

23. Monitor the initial flame. If a plume of gas emanates from the stove manually light the plume with an extended lighter.

24. Photograph the flame during the gasification stage of the stove’s operation.

25. (Optional) Take a spot test of the gases within the stove. Place Testo into the Thermocouple Location B hole shown in Figure A.1.

26. Cease recording data when all relevant combustion phases are observed. (A useful indicator is the CO measurement reading from the Testo. As this value falls at the end of the end of the combustion cycle prepare to stop recording. At 50 ppm CO stop recording thermocouple and Testo data).

27. Remove fuel grate from stove. Clean the grate with a wire brush and dispose of ash/charcoal in a bin. Place the fuel grate back into the stove.

28. Repeat steps 12 – 27 for each experiment.
Appendix E

Controlled Primary Air Testing

E.1 Stove configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary-inlet</td>
<td>Controlled Primary Air</td>
</tr>
<tr>
<td>Secondary-inlet</td>
<td>Shut-off</td>
</tr>
<tr>
<td>Fuel Grate</td>
<td>520 mm from top of stove body</td>
</tr>
<tr>
<td>Chimney</td>
<td>Natural Draft Chimney</td>
</tr>
<tr>
<td>Type of bark chips used</td>
<td>Jefferies Pine</td>
</tr>
<tr>
<td>Location of Testo</td>
<td>1.18 m above stove centreline</td>
</tr>
<tr>
<td>Location of thermocouples</td>
<td>One thermocouple is inserted into thermocouple</td>
</tr>
<tr>
<td></td>
<td>location A as shown in Figure A.4, and another</td>
</tr>
<tr>
<td></td>
<td>thermocouple is inserted into thermocouple</td>
</tr>
<tr>
<td></td>
<td>location B as shown in Figure A.1.</td>
</tr>
</tbody>
</table>
Figure E.1: Stove configuration used for primary air testing
E.2  Testing procedures

1. Examine fuel grate inside stove with a torch. Clean grate if required. Check to see that fuel grate is hanging level.

2. Place a table approximately 1.5 m from the testing stove.

3. Place laptop on table.

4. Place Testo on table, and attach relevant cables and tubes.

5. Position the tip of the Testo’s sampling probe 1.18 m above the top of the cast iron stove body. Ensure sampling probe is over the centre of the stove body.

6. Connect Testo to laptop.

7. Connect thermocouples to computer.

8. Start Testo software.

9. Start thermocouple software.

10. Turn on air extraction system.

11. Check that the extractor hood is set to the ‘open’ position, and that it is free of from any obstructions.

12. Connect primary air hose to primary air inlet

13. Turn on air dryer unit and air compressor unit

14. Turn on airflow regulator and set to 650 kPa

15. Slowly open up all valves to the flowmeter being used.
16. Weigh 700 g of bark chips in a bucket.

17. CAUTION: When conducting the following steps avoid contact with the hot stove.

18. Pour weighed bark chips into the stove.

19. Use a torch to see if fuel is level; if not, level the fuel with a metal ruler.

20. Attach Natural Draft Chimney to top of stove body as seen in Figure E.1.

21. Roll up a piece of paper towel (approximately 190 m x 100 m).

22. Slowly set primary airflow meter to desired airflow with the use of the needle valve.

23. Record air pressure and percentage flow, turn off air supply at valve located immediately after air regulator.

24. Use an infra-red thermometer to measure the stove body temperature (SBT). The location at which this measurement is taken is shown in Figure A.1

25. Monitor the SBT. When the SBT cools to 135 °C start recording Testo and thermocouple data with their respective data acquisition softwares.

26. Slowly turn on primary airflow at valve located immediately after the air regulator.

27. Pour 1 cap of methylated spirits into the stove. Aim to spread the lighter fluid as evenly as possible over the fuel.

28. Re-measure and record the SBT.

29. Light the paper towel prepared in step 21, and drop it into the stove.
30. Monitor the initial flame. If a plume of gas emanates from the stove manually light the plume with an extended lighter.

31. Photograph the flame during the gasification stage of the stove’s operation

32. (Optional) Take a spot test of the gases within the stove. Place Testo into the Thermocouple Location B hole shown in Figure A.1.

33. Cease recording data when all relevant combustion phases are observed. (A useful indicator is the CO measurement reading from the Testo. As this value falls at the end of the end of the combustion cycle prepare to stop recording. At 50 ppm CO stop recording thermocouple and Testo data).

34. Turn off air supply at valve located immediately after air regulator.

35. Remove fuel grate from stove. Clean the grate with a wire brush and dispose of ash/charcoal in a bin. Place the fuel grate back into the stove.

36. Repeat steps 16 – 35 for each experiment.
Appendix F

Controlled Secondary Air Testing

F.1 Stove configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State</th>
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</thead>
<tbody>
<tr>
<td>Primary-inlet</td>
<td>Controlled Primary Air (118 L/min)</td>
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<tr>
<td>Secondary-inlet</td>
<td>Shut-off</td>
</tr>
<tr>
<td>Fuel Grate</td>
<td>520 mm from top of stove body</td>
</tr>
<tr>
<td>Chimney</td>
<td>Controlled Secondary Air Chimney</td>
</tr>
<tr>
<td>Type of bark chips used</td>
<td>Jefferies Pine</td>
</tr>
<tr>
<td>Location of Testo</td>
<td>1.18 m above stove centreline</td>
</tr>
<tr>
<td>Location of thermocouples</td>
<td>One thermocouple is inserted into thermocouple location A as shown in Figure A.6, and another thermocouple is inserted into thermocouple location B as shown in Figure A.1.</td>
</tr>
</tbody>
</table>
Figure F.1: Stove configuration used for controlled secondary air testing
F.2 Testing procedures

1. Examine fuel grate inside stove with a torch. Clean grate if required. Check to see that fuel grate is hanging level.

2. Place a table approximately 1.5 m from the testing stove.

3. Place laptop on table.

4. Place Testo on table, and attach relevant cables and tubes.

5. Position the tip of the Testo’s sampling probe 1.18 m above the top of the cast iron stove body. Ensure sampling probe is over the centre of the stove body.

6. Connect Testo to laptop.

7. Connect thermocouples to computer.

8. Start Testo software.

9. Start thermocouple software.

10. Turn on air extraction system.

11. Check that the extractor hood is set to the ‘open’ position, and that it is free of from any obstructions.

12. Connect primary air hose to primary air inlet

13. Turn on air dryer unit and air compressor unit

14. Turn on airflow regulator and set to 650 kPa

15. Slowly open up all valves to the flowmeters being used.
16. Weigh 700 g of bark chips in a bucket.

17. CAUTION: When conducting the following steps avoid contact with the hot stove.

18. Pour weighed bark chips into the stove.

19. Use a torch to see if fuel is level; if not, level the fuel with a metal ruler.

20. Attach Controlled Secondary Air Chimney to top of stove body as seen in Figure F.1.

21. Attach the 4 air pipes to the 4 quick connection points on the Controlled Secondary Air Chimney.

22. Roll up a piece of paper towel (approximately 190 mm x 100 mm).

23. Slowly set primary airflow meter to 60% airflow at 550 kPa which is 118 L/min and secondary airflow meter to desired airflow with the use of the needle valve, check that neither changes when the other is adjusted.

24. Record air pressures and percentage flows, turn off air supply at valve located immediately after air regulator.

25. Use an infra-red thermometer to measure the stove body temperature (SBT). The location at which this measurement is taken is shown in Figure A.1

26. Monitor the SBT. When the SBT cools to 135 °C start recording Testo and thermocouple data with their respective data acquisition softwares.

27. Slowly turn on airflow at valve located immediately after the air regulator.

28. Pour 1 cap of methylated spirits into the stove. Aim to spread the lighter fluid as evenly as possible over the fuel.
29. Re-measure and record the SBT.

30. Light the paper towel prepared in step 22, and drop it into the stove.

31. Monitor the initial flame. If a plume of gas emanates from the stove manually light the plume with an extended lighter.

32. Photograph the flame during the gasification stage of the stove’s operation.

33. (Optional) Take a spot test of the gases within the stove. Place Testo into the Thermocouple Location B hole shown in Figure A.1.

34. Cease recording data when all relevant combustion phases are observed. (A useful indicator is the CO measurement reading from the Testo. As this value falls at the end of the end of the combustion cycle prepare to stop recording. At 50 ppm CO stop recording thermocouple and Testo data).

35. Turn off air supply at valve located immediately after air regulator.

36. Remove fuel grate from stove. Clean the grate with a wire brush and dispose of ash/charcoal in a bin. Place the fuel grate back into the stove.

37. Repeat steps 16 – 36 for each experiment.
## Appendix G

### Fuel Stack Location Testing

#### G.1 Stove configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary-inlet</td>
<td>Controlled Primary Air</td>
</tr>
<tr>
<td>Secondary-inlet</td>
<td>Shut-off</td>
</tr>
<tr>
<td>Fuel Grate</td>
<td>Varying Locations</td>
</tr>
<tr>
<td>Chimney</td>
<td>Natural Draft Chimney</td>
</tr>
<tr>
<td>Type of bark chips used</td>
<td>Jefferies Pine</td>
</tr>
<tr>
<td>Location of Testo</td>
<td>1.18 m above stove centreline</td>
</tr>
<tr>
<td>Location of thermocouples</td>
<td>One thermocouple is inserted into thermocouple location A as shown in Figure A.4, and another thermocouple is inserted into thermocouple location B as shown in Figure A.1.</td>
</tr>
</tbody>
</table>
Figure G.1: Stove configuration used for fuel stack location testing
G.2 Testing procedures

1. Examine fuel grate inside stove with a torch. Clean grate if required. Check to see that fuel grate is hanging level.

2. Place a table approximately 1.5 m from the testing stove.

3. Place laptop on table.

4. Place Testo on table, and attach relevant cables and tubes.

5. Position the tip of the Testo’s sampling probe 1.18 m above the top of the cast iron stove body. Ensure sampling probe is over the centre of the stove body.

6. Connect Testo to laptop.

7. Connect thermocouples to computer.

8. Start Testo software.

9. Start thermocouple software.

10. Turn on air extraction system.

11. Check that the extractor hood is set to the ‘open’ position, and that it is free of from any obstructions.

12. Connect primary air hose to primary air inlet.

13. Turn on air dryer unit and air compressor unit.

14. Turn on airflow regulator and set to 650 kPa.

15. Slowly open up all valves to the flowmeter being used.
16. Alter fuel great connecting rod lengths to desired length.

17. Weigh 700 g of bark chips in a bucket.

18. CAUTION: When conducting the following steps avoid contact with the hot stove.

19. Pour weighed bark chips into the stove.

20. Use a torch to see if fuel is level; if not, level the fuel with a metal ruler.

21. Attach Natural Draft Chimney to top of stove body as seen in Figure E.1.

22. Roll up a piece of paper towel (approximately 190 mm x 100 mm).

23. Slowly set primary airflow meter to 60 % airflow at 550 kPa which is 118 L/min, with the use of the needle valve.

24. Record air pressure and percentage flow, turn off air supply at valve located immediately after air regulator.

25. Use an infra-red thermometer to measure the stove body temperature (SBT). The location at which this measurement is taken is shown in Figure A.1.

26. Monitor the SBT. When the SBT cools to 135 °C start recording Testo and thermocouple data with their respective data acquisition softwares.

27. Slowly turn on primary airflow at valve located immediately after the air regulator.

28. Pour 1 cap of methylated spirits into the stove. Aim to spread the lighter fluid as evenly as possible over the fuel.

29. Re-measure and record the SBT.
30. Light the paper towel prepared in step 21, and drop it into the stove.

31. Monitor the initial flame. If a plume of gas emanates from the stove manually light the plume with an extended lighter.

32. Photograph the flame during the gasification stage of the stove’s operation.

33. (Optional) Take a spot test of the gases within the stove. Place Testo into the Thermocouple Location B hole shown in Figure A.1.

34. Cease recording data when all relevant combustion phases are observed. (A useful indicator is the CO measurement reading from the Testo. As this value falls at the end of the end of the combustion cycle prepare to stop recording. At 50 ppm CO stop recording thermocouple and Testo data).

35. Turn off air supply at valve located immediately after air regulator.

36. Remove fuel grate from stove. Clean the grate with a wire brush and dispose of ash/charcoal in a bin. Place the fuel grate back into the stove.

37. Repeat steps 16 – 36 for each experiment.
Appendix H

Shaped Fuel Testing

H.1 Stove configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary-inlet</td>
<td>Controlled Primary Air (118 L/min)</td>
</tr>
<tr>
<td>Secondary-inlet</td>
<td>Shut-off</td>
</tr>
<tr>
<td>Fuel Grate</td>
<td>520 mm from top of stove body</td>
</tr>
<tr>
<td>Chimney</td>
<td>Natural Draft Chimney</td>
</tr>
<tr>
<td>Type of Fuel Used</td>
<td>Dried Shaped Dung</td>
</tr>
<tr>
<td>Location of Testo</td>
<td>1.18 m above stove centreline</td>
</tr>
<tr>
<td>Location of thermocouples</td>
<td>One thermocouple is inserted into thermocouple location A as shown in Figure A.4, and another thermocouple is inserted into thermocouple location B as shown in Figure A.1.</td>
</tr>
</tbody>
</table>
Figure H.1: Stove configuration used for shaped fuel testing
1. Examine fuel grate inside stove with a torch. Clean grate if required. Check to see that fuel grate is hanging level.

2. Place a table approximately 1.5 m from the testing stove.

3. Place laptop on table.

4. Place Testo on table, and attach relevant cables and tubes.

5. Position the tip of the Testo’s sampling probe 1.18 m above the top of the cast iron stove body. Ensure sampling probe is over the centre of the stove body.

6. Connect Testo to laptop.

7. Connect thermocouples to computer.

8. Start Testo software.

9. Start thermocouple software.

10. Turn on air extraction system.

11. Check that the extractor hood is set to the ‘open’ position, and that it is free of any obstructions.

12. Connect primary air hose to primary air inlet.

13. Turn on air dryer unit and air compressor unit.

14. Turn on airflow regulator and set to 650 kPa.

15. Slowly open up all valves to the flowmeter being used.

16. CAUTION: When conducting the following step ensure filter mask and gloves are worn.
17. Weigh 700 g of desired dried dung size in a bucket.

18. CAUTION: When conducting the following steps avoid contact with the hot stove.

19. Pour weighed dried dung into the stove.

20. Use a torch to see if fuel is level; if not, level the fuel with a metal ruler.

21. Attach Natural Draft Chimney to top of stove body as seen in Figure E.1.

22. Roll up a piece of paper towel (approximately 190 mm x 100 mm).

23. Slowly set primary airflow meter to 60 % airflow at 550 kPa which is 118 L/min, with the use of the needle valve.

24. Record air pressure and percentage flow, turn off air supply at valve located immediately after air regulator.

25. Use an infra-red thermometer to measure the stove body temperature (SBT). The location at which this measurement is taken is shown in Figure A.1

26. Monitor the SBT. When the SBT cools to 135 °C start recording Testo and thermocouple data with their respective data acquisition softwares.

27. Slowly turn on primary airflow at valve located immediately after the air regulator.

28. Pour 1 cap of methylated spirits into the stove. Aim to spread the lighter fluid as evenly as possible over the fuel.

29. Re-measure and record the SBT.

30. Light the paper towel prepared in step 21, and drop it into the stove.
31. Monitor the initial flame. If a plume of gas emanates from the stove manually
light the plume with an extended lighter.

32. Photograph the flame during the gasification stage of the stove’s operation

33. (Optional) Take a spot test of the gases within the stove. Place Testo into the
Thermocouple Location B hole shown in Figure A.1.

34. Cease recording data when all relevant combustion phases are observed. (A
useful indicator is the CO measurement reading from the Testo. As this value
falls at the end of the end of the combustion cycle prepare to stop recording.
At 50 ppm CO stop recording thermocouple and Testo data).

35. Turn off air supply at valve located immediately after air regulator.

36. CAUTION: When conducting the following step ensure filter mask and gloves
are worn.

37. Remove fuel grate from stove. Clean the grate with a wire brush and dispose
of ash/charcoal in a bin. Place the fuel grate back into the stove.

38. Repeat steps 16 – 37 for each experiment.

H.2 Surface area to volume ratio error

The diameter of each disc was assumed to have varied by less than 10 mm within
a batch. An example calculation is as follows.

\[
\text{Surface area to volume ratio (SAVR)} = \frac{2(r + t)}{rt} \quad (H.2.1)
\]

Equation to calculate surface area to volume ratio
Thickness of disc = \( t \) [mm]

Radius of disc = \( r \) [mm]

Take the 80 mm diameter disc, with thickness 20 mm as an example:

Mean SAVR (diameter = 80 mm) = \( \frac{2(40 + 20)}{40 \times 20} = 0.150 \)

Assume the variation in the disc size is 80 ± 10 mm. The SAVR is calculated for the upper and lower bounds respectively.

SAVR (diameter = 90 mm) = \( \frac{2(45 + 15)}{45 \times 15} = 0.144 \)

SAVR (diameter = 70 mm) = \( \frac{2(35 + 15)}{35 \times 15} = 0.157 \)

Upper error bound = 0.157 - 0.150 = 0.007

Lower error bound = 0.150 - 0.144 = 0.006
Appendix I

Fuel Stack Depth

I.1 Stove configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary-inlet</td>
<td>Controlled Primary Air (118 L/min)</td>
</tr>
<tr>
<td>Secondary-inlet</td>
<td>Shut-off</td>
</tr>
<tr>
<td>Fuel Grate</td>
<td>520 mm from top of stove body with 50 mm layer of small rocks on top</td>
</tr>
<tr>
<td>Chimney</td>
<td>Natural Draft Chimney</td>
</tr>
<tr>
<td>Type of bark chips used</td>
<td>Jefferies Pine</td>
</tr>
<tr>
<td>Location of Testo</td>
<td>1.18 m above stove centreline</td>
</tr>
<tr>
<td>Location of thermocouples</td>
<td>One thermocouple is inserted into thermocouple location A as shown in Figure A.4, and another thermocouple is inserted into thermocouple location B as shown in Figure A.1.</td>
</tr>
</tbody>
</table>
Figure I.1: Stove configuration used for fuel stack depth testing
I.2 Testing procedures

1. Examine fuel grate inside stove with a torch. Clean grate if required. Check to see that fuel grate is hanging level.

2. Place a table approximately 1.5 m from the testing stove.

3. Place laptop on table.

4. Place Testo on table, and attach relevant cables and tubes.

5. Position the tip of the Testo’s sampling probe 1.18 m above the top of the cast iron stove body. Ensure sampling probe is over the centre of the stove body.

6. Connect Testo to laptop.

7. Connect thermocouples to computer.

8. Start Testo software.

9. Start thermocouple software.

10. Turn on air extraction system.

11. Check that the extractor hood is set to the ‘open’ position, and that it is free of from any obstructions.

12. Connect primary air hose to primary air inlet

13. Turn on air dryer unit and air compressor unit

14. Turn on airflow regulator and set to 650 kPa

15. Slowly open up all valves to the flowmeter being used.
16. Weigh 700 g of bark chips in a bucket.

17. CAUTION: When conducting the following steps avoid contact with the hot stove.

18. Add 50 mm layer of small rocks. While adding rocks regularly flatten and measure layer to ensure the desired 50 mm depth is met.

19. Pour weighed bark chips into the stove.

20. Use a torch to see if fuel is level; if not, level the fuel with a metal ruler.

21. Attach Natural Draft Chimney to top of stove body as seen in Figure E.1.

22. Roll up a piece of paper towel (approximately 190 mm x 100 mm).

23. Slowly set primary airflow meter to 60 % airflow at 550 kPa which is 118 L/min, with the use of the needle valve.

24. Record air pressure and percentage flow, turn off air supply at valve located immediately after air regulator.

25. Use an infra-red thermometer to measure the stove body temperature (SBT). The location at which this measurement is taken is shown in Figure A.1

26. Monitor the SBT. When the SBT cools to 135 °C start recording Testo and thermocouple data with their respective data acquisition softwares.

27. Slowly turn on primary airflow at valve located immediately after the air regulator.

28. Pour 1 cap of methylated spirits into the stove. Aim to spread the lighter fluid as evenly as possible over the fuel.

29. Re-measure and record the SBT.
30. Light the paper towel prepared in step 21, and drop it into the stove.

31. Monitor the initial flame. If a plume of gas emanates from the stove manually light the plume with an extended lighter.

32. Photograph the flame during the gasification stage of the stove’s operation.

33. (Optional) Take a spot test of the gases within the stove. Place Testo into the Thermocouple Location B hole shown in Figure A.1.

34. Cease recording data when all relevant combustion phases are observed. (A useful indicator is the CO measurement reading from the Testo. As this value falls at the end of the end of the combustion cycle prepare to stop recording. At 50 ppm CO stop recording thermocouple and Testo data).

35. Turn off air supply at valve located immediately after air regulator.

36. Remove fuel grate from stove. Clean the grate with a wire brush and dispose of ash/charcoal in a bin. Place the fuel grate back into the stove.

37. Repeat steps 16 – 37 for each experiment.
Appendix J

Water Boiling Testing

J.1 Stove configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary-inlet</td>
<td>Varied</td>
</tr>
<tr>
<td>Secondary-inlet</td>
<td>Varied</td>
</tr>
<tr>
<td>Fuel Grate</td>
<td>Varied</td>
</tr>
<tr>
<td>Chimney</td>
<td>Varied</td>
</tr>
<tr>
<td>Type of Fuels used</td>
<td>Jefferies Pine or Dried Shaped Dung</td>
</tr>
<tr>
<td>Location of Testo</td>
<td>1180 mm above stove centreline</td>
</tr>
<tr>
<td>Location of thermocouples</td>
<td>One thermocouple is placed into the water inside the water boiling pot, and another thermocouple is inserted into thermocouple location B as shown in Figure A.1.</td>
</tr>
</tbody>
</table>


J.2 Testing procedures

This testing procedure is used in addition to the testing procedure for the various stove set-ups. Take note of when various steps must be completed.

1. Prior to weighing the fuel add 1 L of tap water to the water boiling pot.

2. Prior to lighting the stove place the water boiling pot 50 mm above the top of the desired chimney. Place one of the thermocouples into the water.

3. After the test run has finished remove thermocouple from water and weigh water boiling pot.

4. Record the final weight of the water boiling pot and minus the weight of the water boiling pot to determine the water lost.

5. Clean and cool down water boiling pot before reusing.
Appendix K

Diffuser Collar Design

K.1 Drawings
Appendix L

Summary Test Data

(...) - Standard deviation of the value above

TWA - Time weighted average

Max - Maximum

Min - Minimum

$T_C$ - Internal chimney temperature

$T_S$ - Internal stove temperature

$T_P$ - Peak temperature

$T_W$ - Water temperature
### Benchmarking

**Normalized Data**

<table>
<thead>
<tr>
<th></th>
<th>Initial</th>
<th>Steady-State</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in Phase [s]</td>
<td>92.6</td>
<td>288</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>(9.93)</td>
<td>(28.6)</td>
<td>(17.1)</td>
</tr>
<tr>
<td>Max CO Peak $[-] \times 10^3$</td>
<td>67.6</td>
<td>—</td>
<td>99.2</td>
</tr>
<tr>
<td></td>
<td>(40)</td>
<td>—</td>
<td>(24.3)</td>
</tr>
<tr>
<td>Time to CO Peak [s]</td>
<td>52.5</td>
<td>—</td>
<td>531</td>
</tr>
<tr>
<td></td>
<td>(11.4)</td>
<td>—</td>
<td>(48.5)</td>
</tr>
<tr>
<td>Max H$_2$ Peak $[-] \times 10^3$</td>
<td>12.1</td>
<td>—</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>(10.8)</td>
<td>—</td>
<td>(6.29)</td>
</tr>
<tr>
<td>Time to H$_2$ Peak [s]</td>
<td>71.1</td>
<td>—</td>
<td>537</td>
</tr>
<tr>
<td></td>
<td>(11.8)</td>
<td>—</td>
<td>(39.8)</td>
</tr>
<tr>
<td>TWA - CO $[-] \times 10^3$</td>
<td>—</td>
<td>3.5</td>
<td>45.3</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(0.608)</td>
<td>(10.1)</td>
</tr>
<tr>
<td>TWA - CO$_2$ $[-] \times 10^3$</td>
<td>—</td>
<td>997</td>
<td>955</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(0.608)</td>
<td>(10.1)</td>
</tr>
<tr>
<td>TWA - NO$_X$ $[-] \times 10^5$</td>
<td>—</td>
<td>59.2</td>
<td>41.2</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(4.77)</td>
<td>(10.1)</td>
</tr>
<tr>
<td>TWA - O$_2$ $[-]$</td>
<td>—</td>
<td>7.31</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(1)</td>
<td>(8.42)</td>
</tr>
<tr>
<td>TWA - H$_2$ $[-] \times 10^5$</td>
<td>—</td>
<td>16.4</td>
<td>3.54</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(18.2)</td>
<td>(1.85)</td>
</tr>
</tbody>
</table>

Table L.1: Benchmarking normalized data for all combustion phases
## Non-Normalized Data

<table>
<thead>
<tr>
<th></th>
<th>Initial</th>
<th>Steady-State</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in Phase [s]</td>
<td>92.6</td>
<td>288</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>(9.93)</td>
<td>(28.6)</td>
<td>(17.1)</td>
</tr>
<tr>
<td>Max CO Peak [-] × 10^3</td>
<td>1250</td>
<td>—</td>
<td>1770</td>
</tr>
<tr>
<td></td>
<td>(728)</td>
<td>—</td>
<td>(593)</td>
</tr>
<tr>
<td>Time to CO Peak [s]</td>
<td>55.4</td>
<td>—</td>
<td>477</td>
</tr>
<tr>
<td></td>
<td>(11.5)</td>
<td>—</td>
<td>(41.9)</td>
</tr>
<tr>
<td>Max H₂ Peak [-] × 10^3</td>
<td>266</td>
<td>—</td>
<td>227</td>
</tr>
<tr>
<td></td>
<td>(233)</td>
<td>—</td>
<td>(129)</td>
</tr>
<tr>
<td>Time to H₂ Peak [s]</td>
<td>71.5</td>
<td>—</td>
<td>491</td>
</tr>
<tr>
<td></td>
<td>(12.4)</td>
<td>—</td>
<td>(42.7)</td>
</tr>
<tr>
<td>TWA - CO [ppm]</td>
<td>—</td>
<td>89.6</td>
<td>618</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(13)</td>
<td>(89.7)</td>
</tr>
<tr>
<td>TWA - CO₂ [%]</td>
<td>—</td>
<td>2.61</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(0.29)</td>
<td>(0.186)</td>
</tr>
<tr>
<td>TWA - NOₓ [ppm]</td>
<td>—</td>
<td>15.7</td>
<td>5.88</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(2.85)</td>
<td>(0.98)</td>
</tr>
<tr>
<td>TWA - O₂ [%]</td>
<td>—</td>
<td>18.7</td>
<td>19.7</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(0.298)</td>
<td>(0.158)</td>
</tr>
<tr>
<td>TWA - H₂ [ppm]</td>
<td>—</td>
<td>4.31</td>
<td>42.8</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(4.73)</td>
<td>(21.9)</td>
</tr>
</tbody>
</table>

Table L.2: Benchmarking non-normalized data for all combustion phases
# Primary Air

## Initial Phase

<table>
<thead>
<tr>
<th>Normalized Data [L/min]</th>
<th>78</th>
<th>98</th>
<th>118</th>
<th>137</th>
<th>Natural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in Phase [s]</td>
<td>96.6</td>
<td>74.3</td>
<td>74.2</td>
<td>80.4</td>
<td>92.6</td>
</tr>
<tr>
<td></td>
<td>(13.8)</td>
<td>(19.4)</td>
<td>(14.6)</td>
<td>(12.8)</td>
<td>(9.93)</td>
</tr>
<tr>
<td>Max CO Peak $[-] \times 10^3$</td>
<td>130</td>
<td>53.5</td>
<td>65.9</td>
<td>35.7</td>
<td>67.6</td>
</tr>
<tr>
<td></td>
<td>(66.3)</td>
<td>(28.8)</td>
<td>(39.6)</td>
<td>(11.8)</td>
<td>(40)</td>
</tr>
<tr>
<td>Time to CO Peak [s]</td>
<td>51.6</td>
<td>28.5</td>
<td>36.5</td>
<td>44.4</td>
<td>52.5</td>
</tr>
<tr>
<td></td>
<td>(14.7)</td>
<td>(9.15)</td>
<td>(12.1)</td>
<td>(10.7)</td>
<td>(11.4)</td>
</tr>
<tr>
<td>Max H$_2$ Peak $[-] \times 10^3$</td>
<td>25.6</td>
<td>7.85</td>
<td>12</td>
<td>4.05</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>(15.2)</td>
<td>(6.8)</td>
<td>(8.83)</td>
<td>(2.56)</td>
<td>(10.8)</td>
</tr>
<tr>
<td>Time to H$_2$ Peak [s]</td>
<td>69.8</td>
<td>45.5</td>
<td>54.3</td>
<td>62.7</td>
<td>71.1</td>
</tr>
<tr>
<td></td>
<td>(14.6)</td>
<td>(13.4)</td>
<td>(11.7)</td>
<td>(10.1)</td>
<td>(11.8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-Normalized Data [L/min]</th>
<th>78</th>
<th>98</th>
<th>118</th>
<th>137</th>
<th>Natural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in Phase [s]</td>
<td>96.6</td>
<td>74.3</td>
<td>74.2</td>
<td>80.4</td>
<td>92.6</td>
</tr>
<tr>
<td></td>
<td>(13.8)</td>
<td>(19.4)</td>
<td>(14.6)</td>
<td>(12.8)</td>
<td>(9.93)</td>
</tr>
<tr>
<td>Max CO Peak [ppm]</td>
<td>1830</td>
<td>1010</td>
<td>1400</td>
<td>628</td>
<td>1250</td>
</tr>
<tr>
<td></td>
<td>(828)</td>
<td>(641)</td>
<td>(842)</td>
<td>(187)</td>
<td>(728)</td>
</tr>
<tr>
<td>Time to CO Peak [s]</td>
<td>55.8</td>
<td>42.5</td>
<td>40.5</td>
<td>47.9</td>
<td>55.4</td>
</tr>
<tr>
<td></td>
<td>(13.7)</td>
<td>(18.7)</td>
<td>(12)</td>
<td>(10.1)</td>
<td>(11.5)</td>
</tr>
<tr>
<td>Max H$_2$ Peak [ppm]</td>
<td>458</td>
<td>202</td>
<td>340</td>
<td>89.1</td>
<td>266</td>
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<td>(172)</td>
<td>(264)</td>
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<td>(233)</td>
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<tr>
<td>Time to H$_2$ Peak [s]</td>
<td>70.6</td>
<td>58</td>
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<td>63.6</td>
<td>71.5</td>
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<td>(14.5)</td>
<td>(18.8)</td>
<td>(12)</td>
<td>(10.8)</td>
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Table L.3: Primary air data for initial combustion phase
## Steady-State Phase

### Normalized Data [L/min]

<table>
<thead>
<tr>
<th>Time in Phase [s]</th>
<th>78</th>
<th>98</th>
<th>118</th>
<th>137</th>
<th>Natural</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>286</td>
<td>227</td>
<td>184</td>
<td>216</td>
<td>288</td>
</tr>
<tr>
<td></td>
<td>(120)</td>
<td>(66.8)</td>
<td>(17.2)</td>
<td>(20.7)</td>
<td>(28.6)</td>
</tr>
<tr>
<td>TWA - CO [-] $\times 10^3$</td>
<td>6.85</td>
<td>3.71</td>
<td>2.97</td>
<td>3.09</td>
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<td></td>
<td>(2.33)</td>
<td>(0.773)</td>
<td>(0.685)</td>
<td>(0.817)</td>
<td>(0.608)</td>
</tr>
<tr>
<td>TWA - CO$_2$ [-] $\times 10^3$</td>
<td>993</td>
<td>996</td>
<td>997</td>
<td>997</td>
<td>997</td>
</tr>
<tr>
<td></td>
<td>(2.33)</td>
<td>(0.773)</td>
<td>(0.685)</td>
<td>(0.817)</td>
<td>(0.608)</td>
</tr>
<tr>
<td>TWA - NO$_X$ [-] $\times 10^5$</td>
<td>54.5</td>
<td>63.7</td>
<td>68.4</td>
<td>64.4</td>
<td>59.2</td>
</tr>
<tr>
<td></td>
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<td>(0.928)</td>
<td>(3.3)</td>
<td>(3.51)</td>
<td>(4.77)</td>
</tr>
<tr>
<td>TWA - O$_2$ [-]</td>
<td>7.7</td>
<td>5.96</td>
<td>4.61</td>
<td>6.91</td>
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<td>16.4</td>
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<td>(14.8)</td>
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### Non-Normalized Data [L/min]

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<th>118</th>
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<th>Natural</th>
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<tbody>
<tr>
<td></td>
<td>286</td>
<td>227</td>
<td>184</td>
<td>216</td>
<td>288</td>
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<tr>
<td></td>
<td>(120)</td>
<td>(66.8)</td>
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<td>(20.7)</td>
<td>(28.6)</td>
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<td>166</td>
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<td>109</td>
<td>85</td>
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<td>(32.5)</td>
<td>(33.8)</td>
<td>(22.6)</td>
<td>(13)</td>
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<tr>
<td>TWA - CO$_2$ [%]</td>
<td>2.45</td>
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<td>20.4</td>
<td>24.9</td>
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<td>(1.22)</td>
<td>(2.85)</td>
</tr>
<tr>
<td>TWA - O$_2$ [%]</td>
<td>18.8</td>
<td>18</td>
<td>17.3</td>
<td>18.4</td>
<td>18.7</td>
</tr>
<tr>
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<td>(0.445)</td>
<td>(0.0596)</td>
<td>(0.105)</td>
<td>(0.298)</td>
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<td>TWA - H$_2$ [ppm]</td>
<td>13.8</td>
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<td>13.7</td>
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<td>(4.22)</td>
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<td>(1.39)</td>
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Table L.4: Primary air data for steady-state combustion phase
### Final Phase

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<th>137</th>
<th>Natural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in Phase [s]</td>
<td>219</td>
<td>301</td>
<td>344</td>
<td>305</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>(121)</td>
<td>(84.4)</td>
<td>(25.6)</td>
<td>(17.1)</td>
<td>(17.1)</td>
</tr>
<tr>
<td>Max CO Peak $[-] \times 10^3$</td>
<td>86.3</td>
<td>90.4</td>
<td>128</td>
<td>173</td>
<td>99.2</td>
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<tr>
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<td>(50.6)</td>
<td>(23.1)</td>
<td>(36)</td>
<td>(47.7)</td>
<td>(24.3)</td>
</tr>
<tr>
<td>Time to CO Peak [s]</td>
<td>535</td>
<td>405</td>
<td>369</td>
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<td>(122)</td>
<td>(30.9)</td>
<td>(86.2)</td>
<td>(48.5)</td>
</tr>
<tr>
<td>Max H$_2$ Peak $[-] \times 10^3$</td>
<td>26.1</td>
<td>20.7</td>
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<td>(9.3)</td>
<td>(7.98)</td>
<td>(6.29)</td>
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<tr>
<td>Time to H$_2$ Peak [s]</td>
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<td>420</td>
<td>383</td>
<td>415</td>
<td>537</td>
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<tr>
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<td>(122)</td>
<td>(31.5)</td>
<td>(84.9)</td>
<td>(39.8)</td>
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<tr>
<td>TWA - CO $[-] \times 10^3$</td>
<td>35.8</td>
<td>34.9</td>
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<td>66.2</td>
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<td>(6.81)</td>
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<tr>
<td>TWA - CO$_2$ $[-] \times 10^3$</td>
<td>964</td>
<td>965</td>
<td>951</td>
<td>934</td>
<td>955</td>
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<td>(13.2)</td>
<td>(6.75)</td>
<td>(5.04)</td>
<td>(6.81)</td>
<td>(10.1)</td>
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<td>TWA - NO$_X$ $[-] \times 10^5$</td>
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<td>(9.53)</td>
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<td>(8.66)</td>
<td>(10.1)</td>
</tr>
<tr>
<td>TWA - O$_2$ $[-]$</td>
<td>13.6</td>
<td>15.9</td>
<td>18.4</td>
<td>25.8</td>
<td>19.5</td>
</tr>
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<td>(4.48)</td>
<td>(1.13)</td>
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<td>TWA - H$_2$ $[-] \times 10^5$</td>
<td>5.29</td>
<td>2.77</td>
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Table L.5: Primary air normalized data for final combustion phase
### Table L.6: Primary air non-normalized data for final combustion phase

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<th>Non-Normalized Data [L/min]</th>
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<th>118</th>
<th>137</th>
<th>Natural</th>
</tr>
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<tbody>
<tr>
<td>Time in Phase [s]</td>
<td>219</td>
<td>301</td>
<td>344</td>
<td>305</td>
<td>222</td>
</tr>
<tr>
<td>(121) (84.4) (25.6) (17.1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max CO Peak [ppm]</td>
<td>1100</td>
<td>1250</td>
<td>1630</td>
<td>1740</td>
<td>1770</td>
</tr>
<tr>
<td>(545) (142) (373) (362) (593)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to CO Peak [s]</td>
<td>535</td>
<td>403</td>
<td>368</td>
<td>367</td>
<td>477</td>
</tr>
<tr>
<td>(45.3) (122) (31.2) (24.1) (41.9)</td>
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<td></td>
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<tr>
<td>Max H\textsubscript{2} Peak [ppm]</td>
<td>271</td>
<td>267</td>
<td>333</td>
<td>304</td>
<td>227</td>
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<tr>
<td>Time to H\textsubscript{2} Peak [s]</td>
<td>543</td>
<td>419</td>
<td>383</td>
<td>381</td>
<td>491</td>
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<tr>
<td>(32.4) (123) (31.2) (23.5) (42.7)</td>
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<td></td>
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<tr>
<td>TWA - CO [ppm]</td>
<td>537</td>
<td>449</td>
<td>540</td>
<td>551</td>
<td>618</td>
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<td>(201) (55.5) (42.1) (39.2) (89.7)</td>
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<td></td>
</tr>
<tr>
<td>TWA - CO\textsubscript{2} [%]</td>
<td>1.55</td>
<td>1.36</td>
<td>1.17</td>
<td>0.817</td>
<td>1.49</td>
</tr>
<tr>
<td>(0.144) (0.4) (0.0848) (0.112) (0.186)</td>
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<td>TWA - NO\textsubscript{X} [ppm]</td>
<td>7.22</td>
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<td>(1.02) (2.72) (1.25) (0.87) (0.98)</td>
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<td></td>
</tr>
<tr>
<td>TWA - O\textsubscript{2} [%]</td>
<td>19.6</td>
<td>19.7</td>
<td>19.9</td>
<td>20.2</td>
<td>19.7</td>
</tr>
<tr>
<td>(0.207) (0.356) (0.104) (0.123) (0.158)</td>
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<td></td>
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<tr>
<td>TWA - H\textsubscript{2} [ppm]</td>
<td>65.9</td>
<td>37.3</td>
<td>47</td>
<td>34.1</td>
<td>42.8</td>
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<tr>
<td>(37.4) (16.9) (13.9) (10.1) (21.9)</td>
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</table>
## Secondary Air

### Initial Phase

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<th></th>
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<th>Non-Normalized Data [L/min]</th>
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<td></td>
<td>328 410 492 574 Natural</td>
<td>328 410 492 574 Natural</td>
</tr>
<tr>
<td>Time in Phase [s]</td>
<td>56 60.8 59.5 50 92.6</td>
<td>56 60.8 59.5 50 92.6</td>
</tr>
<tr>
<td></td>
<td>(14.2) (19) (20.5) (8.89) (9.93)</td>
<td>(14.2) (19) (20.5) (8.89) (9.93)</td>
</tr>
<tr>
<td>Max CO Peak [−] × 10³</td>
<td>14.9 14 15.5 7.96 67.6</td>
<td>14.9 14 15.5 7.96 67.6</td>
</tr>
<tr>
<td></td>
<td>(4.51) (1.69) (8.93) (1.91) (40)</td>
<td>(4.51) (1.69) (8.93) (1.91) (40)</td>
</tr>
<tr>
<td>Time to CO Peak [s]</td>
<td>34.7 36.8 29 25.3 52.5</td>
<td>34.7 36.8 29 25.3 52.5</td>
</tr>
<tr>
<td></td>
<td>(11.2) (18.8) (7.48) (3.21) (11.4)</td>
<td>(11.2) (18.8) (7.48) (3.21) (11.4)</td>
</tr>
<tr>
<td>Max H₂ Peak [−] × 10³</td>
<td>0.712 1.15 1.17 0.23 12.1</td>
<td>0.712 1.15 1.17 0.23 12.1</td>
</tr>
<tr>
<td></td>
<td>(0.668) (0.532) (0.783) (0.398) (10.8)</td>
<td>(0.668) (0.532) (0.783) (0.398) (10.8)</td>
</tr>
<tr>
<td>Time to H₂ Peak [s]</td>
<td>38 54.3 36.3 19 71.1</td>
<td>38 54.3 36.3 19 71.1</td>
</tr>
<tr>
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<td>(32.1) (19.2) (25.8) (31.2) (11.8)</td>
<td>(32.1) (19.2) (25.8) (31.2) (11.8)</td>
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Table L.7: Secondary air data for initial combustion phase
### Steady-State Phase

<table>
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<th>Non-Normalized Data [L/min]</th>
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<td><strong>Time in Phase [s]</strong></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>328</td>
<td>410</td>
</tr>
<tr>
<td></td>
<td>492</td>
<td>574</td>
</tr>
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</tr>
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<td>276</td>
<td>265</td>
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<td>278</td>
<td>243</td>
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<td>(20.6)</td>
<td>(25.1)</td>
</tr>
<tr>
<td></td>
<td>(12.5)</td>
<td>(29.5)</td>
</tr>
<tr>
<td></td>
<td>(28.6)</td>
<td></td>
</tr>
<tr>
<td><strong>TWA - CO [-] × 10^3</strong></td>
<td>6.23</td>
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<td>0.9</td>
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</tr>
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<td>(1.58)</td>
<td>(1.48)</td>
</tr>
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<td>(0.295)</td>
<td>(0.281)</td>
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<td>(0.608)</td>
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</tr>
<tr>
<td><strong>TWA - CO₂ [-] × 10^3</strong></td>
<td>994</td>
<td>998</td>
</tr>
<tr>
<td></td>
<td>999</td>
<td>999</td>
</tr>
<tr>
<td></td>
<td>997</td>
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<td></td>
<td>(1.58)</td>
<td>(1.48)</td>
</tr>
<tr>
<td></td>
<td>(0.295)</td>
<td>(0.281)</td>
</tr>
<tr>
<td></td>
<td>(0.608)</td>
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</tr>
<tr>
<td><strong>TWA - NOₓ [-] × 10^5</strong></td>
<td>48.1</td>
<td>50.6</td>
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<td>57.4</td>
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<td>(4.77)</td>
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<tr>
<td><strong>TWA - O₂ [-]</strong></td>
<td>8.92</td>
<td>8.25</td>
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<td>10.7</td>
<td>11.5</td>
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<td>7.31</td>
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<tr>
<td><strong>TWA - H₂ [-] × 10^5</strong></td>
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<td>11.9</td>
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<td>0.758</td>
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<td>(16.9)</td>
</tr>
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Table L.8: Secondary air data for steady-state combustion phase
## Final Phase

<table>
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<tr>
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<tr>
<td></td>
<td>328</td>
</tr>
<tr>
<td><strong>Time in Phase [s]</strong></td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>(6.43)</td>
</tr>
<tr>
<td><strong>Max CO Peak [-] (\times 10^3)</strong></td>
<td>127</td>
</tr>
<tr>
<td></td>
<td>(32)</td>
</tr>
<tr>
<td><strong>Time to CO Peak [s]</strong></td>
<td>600</td>
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<tr>
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<td>(0)</td>
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<tr>
<td><strong>Max H(_2) Peak [-] (\times 10^3)</strong></td>
<td>9.71</td>
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<tr>
<td></td>
<td>(10.7)</td>
</tr>
<tr>
<td><strong>Time to H(_2) Peak [s]</strong></td>
<td>550</td>
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<tr>
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<td>(48.1)</td>
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<tr>
<td><strong>TWA - CO [-] (\times 10^3)</strong></td>
<td>60.3</td>
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<tr>
<td></td>
<td>(15.5)</td>
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<tr>
<td><strong>TWA - CO(_2) [-] (\times 10^3)</strong></td>
<td>940</td>
</tr>
<tr>
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<td>(15.5)</td>
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<tr>
<td><strong>TWA - NO(_x) [-] (\times 10^5)</strong></td>
<td>26.4</td>
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<td>(9.85)</td>
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<tr>
<td><strong>TWA - O(_2) [-]</strong></td>
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<td>(3.3)</td>
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<td><strong>TWA - H(_2) [-] (\times 10^5)</strong></td>
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<td>(0.751)</td>
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Table L.9: Secondary air normalized data for final combustion phase
### Table L.10: Secondary air non-normalized data for final combustion phase

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<th>Non-Normalized Data [L/min]</th>
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<th>574</th>
<th>Natural</th>
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<td>Time in Phase [s]</td>
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<td>(6.43)</td>
<td>(9.59)</td>
<td>(23.1)</td>
<td>(32.6)</td>
<td>(32.6)</td>
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<tr>
<td>Max CO Peak [ppm]</td>
<td>892</td>
<td>743</td>
<td>523</td>
<td>526</td>
<td>1770</td>
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<td>(216)</td>
<td>(301)</td>
<td>(108)</td>
<td>(182)</td>
<td>(593)</td>
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<td>Time to CO Peak [s]</td>
<td>535</td>
<td>524</td>
<td>598</td>
<td>600</td>
<td>477</td>
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<td>(57.8)</td>
<td>(2.45)</td>
<td>(0)</td>
<td>(41.9)</td>
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<tr>
<td>Max H(_2) Peak [ppm]</td>
<td>61.3</td>
<td>68.6</td>
<td>25.4</td>
<td>3.36</td>
<td>227</td>
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<tr>
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<td>(67.4)</td>
<td>(61.1)</td>
<td>(24.6)</td>
<td>(2.16)</td>
<td>(129)</td>
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<tr>
<td>Time to H(_2) Peak [s]</td>
<td>550</td>
<td>521</td>
<td>497</td>
<td>444</td>
<td>491</td>
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<td>(93.6)</td>
<td>(109)</td>
<td>(135)</td>
<td>(42.7)</td>
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<tr>
<td>TWA - CO [ppm]</td>
<td>437</td>
<td>343</td>
<td>263</td>
<td>203</td>
<td>618</td>
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<td>(31.4)</td>
<td>(45.7)</td>
<td>(75.7)</td>
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<td>(89.7)</td>
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<td>TWA - CO(_2) [%]</td>
<td>0.764</td>
<td>0.842</td>
<td>0.725</td>
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<td>(0.221)</td>
<td>(0.0595)</td>
<td>(0.0351)</td>
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<td>TWA - NO(_X) [ppm]</td>
<td>2.22</td>
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<td>2.14</td>
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<td>5.88</td>
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<td>(1.29)</td>
<td>(0.189)</td>
<td>(0.272)</td>
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<tr>
<td>TWA - O(_2) [%]</td>
<td>20.4</td>
<td>20.4</td>
<td>20.5</td>
<td>20.6</td>
<td>19.7</td>
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<td>(0.0873)</td>
<td>(0.0376)</td>
<td>(0.0343)</td>
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<td>TWA - H(_2) [ppm]</td>
<td>6.76</td>
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<td>6.05</td>
<td>0.212</td>
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<td>(5.09)</td>
<td>(7.38)</td>
<td>(0.205)</td>
<td>(21.9)</td>
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Fuel Size Testing

Initial Phase

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<tr>
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<th>Non-Normalized Data [L/min]</th>
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<tr>
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<td>0.15 0.19 0.22</td>
<td>0.15 0.19 0.22</td>
</tr>
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<td>Time in Phase [s]</td>
<td>113 95.3 25.7</td>
<td>113 95.3 25.7</td>
</tr>
<tr>
<td></td>
<td>(25.8) (18.5) (9.81)</td>
<td>(25.8) (18.5) (9.81)</td>
</tr>
<tr>
<td>Max CO Peak [−] × 10³</td>
<td>81.7 104 8.73</td>
<td>1080 1020 33.3</td>
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<tr>
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<td>(27) (24.4) (3.75)</td>
<td>(347) (185) (10.8)</td>
</tr>
<tr>
<td>Time to CO Peak [s]</td>
<td>52 45 21</td>
<td>58 51.7 21.3</td>
</tr>
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<td>(5.57) (12.5) (5.57)</td>
<td>(11.5) (10.1) (5.13)</td>
</tr>
<tr>
<td>Max H₂ Peak [−] × 10³</td>
<td>12 19.1 —</td>
<td>196 229 —</td>
</tr>
<tr>
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<td>(9.04) (10.7) —</td>
<td>(145) (85.8) —</td>
</tr>
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<td>Time to H₂ Peak [s]</td>
<td>73 68.3 —</td>
<td>74.3 68 —</td>
</tr>
<tr>
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<td>(14.2) (11.7) —</td>
<td>(12.9) (11.4) —</td>
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Table L.11: Varying fuel size data for initial combustion phase
### Steady-State Phase

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<th>Non-Normalized Data [L/min]</th>
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<td><strong>Time in Phase [s]</strong></td>
<td>104</td>
<td>125</td>
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<td></td>
<td>(13.3)</td>
<td>(1.53)</td>
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<tr>
<td><strong>TWA - CO [-] × 10³</strong></td>
<td>8.32</td>
<td>10.8</td>
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<tr>
<td></td>
<td>(0.199)</td>
<td>(2.62)</td>
</tr>
<tr>
<td><strong>TWA - CO₂ [-] × 10³</strong></td>
<td>992</td>
<td>989</td>
</tr>
<tr>
<td></td>
<td>(0.199)</td>
<td>(2.62)</td>
</tr>
<tr>
<td><strong>TWA - NOX [-] × 10⁵</strong></td>
<td>401</td>
<td>359</td>
</tr>
<tr>
<td></td>
<td>(54)</td>
<td>(20.4)</td>
</tr>
<tr>
<td><strong>TWA - O₂ [-]</strong></td>
<td>—</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>(2.16)</td>
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<tr>
<td><strong>TWA - H₂ [-] × 10⁵</strong></td>
<td>39.9</td>
<td>22.7</td>
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<td>(61.9)</td>
<td>(18.6)</td>
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Table L.12: Varying fuel size data for steady-state combustion phase
### Final Phase

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<th>Normalized Data [mm/mm]</th>
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<tr>
<td>Time in Phase [s]</td>
<td>185</td>
<td>181</td>
<td>50</td>
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<tr>
<td>(12.5)</td>
<td>(17)</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Max CO Peak [-] × 10^3</td>
<td>168</td>
<td>147</td>
<td>43.3</td>
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<td>(30.6)</td>
<td>(10.6)</td>
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<tr>
<td>Time to CO Peak [s]</td>
<td>296</td>
<td>301</td>
<td>367</td>
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<td>(1.53)</td>
<td>(28.3)</td>
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<tr>
<td>Max H\textsubscript{2} Peak [-] × 10^3</td>
<td>66.3</td>
<td>50.6</td>
<td>11</td>
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<tr>
<td>(7.61)</td>
<td>(20.9)</td>
<td>(4.96)</td>
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</tr>
<tr>
<td>Time to H\textsubscript{2} Peak [s]</td>
<td>310</td>
<td>324</td>
<td>352</td>
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<tr>
<td>(10)</td>
<td>(16.8)</td>
<td>(1.15)</td>
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</tr>
<tr>
<td>TWA - CO [-] × 10^3</td>
<td>53.1</td>
<td>66.8</td>
<td>36.4</td>
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<td>(5.71)</td>
<td>(16)</td>
<td>(5.24)</td>
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</tr>
<tr>
<td>TWA - CO\textsubscript{2} [-] × 10^3</td>
<td>947</td>
<td>933</td>
<td>964</td>
</tr>
<tr>
<td>(5.71)</td>
<td>(16)</td>
<td>(5.24)</td>
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<tr>
<td>TWA - NO\textsubscript{X} [-] × 10^5</td>
<td>174</td>
<td>158</td>
<td>118</td>
</tr>
<tr>
<td>(13.3)</td>
<td>(10.6)</td>
<td>(22.8)</td>
<td></td>
</tr>
<tr>
<td>TWA - O\textsubscript{2} [-]</td>
<td>—</td>
<td>33</td>
<td>—</td>
</tr>
<tr>
<td>—</td>
<td>—</td>
<td>(2.42)</td>
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</tr>
<tr>
<td>TWA - H\textsubscript{2} [-] × 10^5</td>
<td>15.7</td>
<td>16.4</td>
<td>8.93</td>
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<td>(2.52)</td>
<td>(7.7)</td>
<td>(3.7)</td>
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Table L.13: Varying fuel size normalized data for final combustion phase
### Table L.14: Varying fuel size non-normalized data for final combustion phase

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<th>Non-Normalized Data [L/min]</th>
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<td>0.19</td>
<td>0.22</td>
</tr>
<tr>
<td>Time in Phase [s]</td>
<td>185</td>
<td>181</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(12.5)</td>
<td>(17)</td>
<td></td>
<td></td>
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<tr>
<td>Max CO Peak [ppm]</td>
<td>1400</td>
<td>919</td>
<td>295</td>
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<tr>
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<td>(106)</td>
<td>(226)</td>
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<tr>
<td>Time to CO Peak [s]</td>
<td>295</td>
<td>298</td>
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<td></td>
<td>(10)</td>
<td>(4.73)</td>
<td>(24.5)</td>
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<tr>
<td>Max H₂ Peak [ppm]</td>
<td>527</td>
<td>294</td>
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<tr>
<td>Time to H₂ Peak [s]</td>
<td>310</td>
<td>321</td>
<td>369</td>
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<tr>
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<td>(10.5)</td>
<td>(11.9)</td>
<td>(27.2)</td>
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<tr>
<td>TWA - CO [ppm]</td>
<td>471</td>
<td>418</td>
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<td>(61.9)</td>
<td>(36.9)</td>
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<td>TWA - CO₂ [%]</td>
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<td>0.634</td>
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<td>(0.00973)</td>
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<tr>
<td>TWA - NOₓ [ppm]</td>
<td>19.7</td>
<td>12.5</td>
<td>8.61</td>
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<td>(0.46)</td>
<td>(1.6)</td>
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<tr>
<td>TWA - O₂ [%]</td>
<td>—</td>
<td>20.5</td>
<td>—</td>
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<td>—</td>
<td>(0.0565)</td>
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<td>TWA - H₂ [ppm]</td>
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## Separation Distance

### Initial Phase

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<th>Non-Normalized Data [mm]</th>
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<td>Max CO Peak [−] ( \times 10^3 )</td>
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<td>Time to H(_2) Peak [s]</td>
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Table L.15: Separation distance data for initial combustion phase
### Steady-State Phase

#### Normalized Data [mm]

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<th>Time in Phase [s]</th>
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<th>270</th>
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<td></td>
<td>419</td>
<td>398</td>
<td>258</td>
<td>188</td>
</tr>
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<td>(29.3)</td>
<td>(25.1)</td>
<td>(17.1)</td>
<td>(20.3)</td>
</tr>
<tr>
<td>TWA - CO [-] $\times 10^3$</td>
<td>4.91</td>
<td>3.37</td>
<td>2.95</td>
<td>2.55</td>
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<td>(1.63)</td>
<td>(0.17)</td>
<td>(0.441)</td>
<td>(0.209)</td>
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<td>TWA - CO$_2$ [-] $\times 10^3$</td>
<td>995</td>
<td>997</td>
<td>997</td>
<td>997</td>
</tr>
<tr>
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<td>(0.17)</td>
<td>(0.441)</td>
<td>(0.209)</td>
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<tr>
<td>TWA - NO$_X$ [-] $\times 10^5$</td>
<td>57.7</td>
<td>76.6</td>
<td>71</td>
<td>69.2</td>
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<td>(20.5)</td>
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<td>(3.87)</td>
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<td>TWA - O$_2$ [-]</td>
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<td>—</td>
<td>—</td>
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</tr>
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<td>TWA - H$_2$ [-] $\times 10^5$</td>
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<td>0.271</td>
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<td>(0.136)</td>
<td>(0.204)</td>
<td>(0.00887)</td>
<td>(0.315)</td>
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</table>

#### Non-Normalized Data [mm]

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<tr>
<th>Time in Phase [s]</th>
<th>80</th>
<th>170</th>
<th>270</th>
<th>370</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>419</td>
<td>398</td>
<td>258</td>
<td>188</td>
</tr>
<tr>
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<td>(29.3)</td>
<td>(25.1)</td>
<td>(17.1)</td>
<td>(20.3)</td>
</tr>
<tr>
<td>TWA - CO [ppm]</td>
<td>128</td>
<td>92.9</td>
<td>84.7</td>
<td>88</td>
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<td>(35.9)</td>
<td>(6.6)</td>
<td>(14.2)</td>
<td>(7.95)</td>
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<tr>
<td>TWA - CO$_2$ [%]</td>
<td>2.6</td>
<td>2.45</td>
<td>2.99</td>
<td>3.49</td>
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<td>(0.0998)</td>
<td>(0.0954)</td>
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<td>TWA - NO$_X$ [ppm]</td>
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<td>17.4</td>
<td>21.6</td>
<td>24.2</td>
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<td>(3.36)</td>
<td>(0.636)</td>
<td>(1.62)</td>
<td>(1.46)</td>
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<tr>
<td>TWA - O$_2$ [%]</td>
<td>—</td>
<td>—</td>
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<tr>
<td>TWA - H$_2$ [ppm]</td>
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Table L.16: Separation distance data for steady-state combustion phase
## Final Phase

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<tr>
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<th>Normalized Data [mm]</th>
<th>80</th>
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<th>370</th>
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<tbody>
<tr>
<td>Time in Phase [s]</td>
<td></td>
<td>182</td>
<td>203</td>
<td>277</td>
<td>344</td>
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<tr>
<td></td>
<td></td>
<td>(29.3)</td>
<td>(25.1)</td>
<td>(22.3)</td>
<td>(16.1)</td>
</tr>
<tr>
<td>Max CO Peak $[-] \times 10^3$</td>
<td></td>
<td>104</td>
<td>117</td>
<td>138</td>
<td>121</td>
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<tr>
<td></td>
<td></td>
<td>(12.9)</td>
<td>(15.4)</td>
<td>(28.6)</td>
<td>(44.2)</td>
</tr>
<tr>
<td>Time to CO Peak [s]</td>
<td></td>
<td>558</td>
<td>492</td>
<td>396</td>
<td>372</td>
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<tr>
<td></td>
<td></td>
<td>(36)</td>
<td>(16.6)</td>
<td>(10.3)</td>
<td>(23.4)</td>
</tr>
<tr>
<td>Max H$_2$ Peak $[-] \times 10^3$</td>
<td></td>
<td>14.8</td>
<td>22</td>
<td>21.5</td>
<td>27.4</td>
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<tr>
<td></td>
<td></td>
<td>(2.32)</td>
<td>(1.49)</td>
<td>(5.2)</td>
<td>(11.1)</td>
</tr>
<tr>
<td>Time to H$_2$ Peak [s]</td>
<td></td>
<td>572</td>
<td>505</td>
<td>410</td>
<td>386</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>(14.8)</td>
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<td>—</td>
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<td>TWA - H$_2$ $[-] \times 10^5$</td>
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Table L.17: Separation distance normalized data for final combustion phase
## Table L.18: Separation distance non-normalized data for final combustion phase

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<th>Non-Normalized Data [mm]</th>
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<tr>
<td>Time in Phase [s]</td>
<td></td>
<td>182</td>
<td>203</td>
<td>277</td>
<td>344</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(29.3)</td>
<td>(25.1)</td>
<td>(22.3)</td>
<td>(16.1)</td>
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<tr>
<td>Max CO Peak [ppm]</td>
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<td>1130</td>
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<tr>
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<td></td>
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<td>(274)</td>
<td>(220)</td>
<td>(437)</td>
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<td>Time to CO Peak [s]</td>
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<td>395</td>
<td>372</td>
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<tr>
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<td>(14.6)</td>
<td>(10.4)</td>
<td>(23.4)</td>
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<tr>
<td>Max H₂ Peak [ppm]</td>
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<td>232</td>
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<td>(32.9)</td>
<td>(100)</td>
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<td>505</td>
<td>409</td>
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<td>591</td>
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<td>539</td>
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<td>(73.5)</td>
<td>(45)</td>
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<tr>
<td>TWA - CO₂ [%]</td>
<td></td>
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<td>1.05</td>
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<td>1.19</td>
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<tr>
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<td>(0.0401)</td>
<td>(0.098)</td>
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<td>TWA - NOₓ [ppm]</td>
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<td>(0.54)</td>
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</tr>
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<td>TWA - H₂ [ppm]</td>
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<td>19.4</td>
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<td>42.1</td>
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## Temperature

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<tr>
<td>78 [L/min]</td>
<td>439</td>
<td>73.4</td>
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<td>446</td>
<td>520</td>
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<td>328</td>
<td>542</td>
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<td>(24.7)</td>
<td>(115)</td>
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<tr>
<td>118 [L/min]</td>
<td>479</td>
<td>56</td>
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<td>280</td>
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<td>(10.8)</td>
<td>(32.4)</td>
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<td>315</td>
<td>535</td>
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<td>(51.7)</td>
<td>(12.9)</td>
<td>(11.8)</td>
<td>(39.1)</td>
<td>(8.88)</td>
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## Secondary Air

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<tr>
<td>328 [L/min]</td>
<td>567</td>
<td>50.8</td>
<td>354</td>
<td>281</td>
<td>861</td>
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<td>(24.5)</td>
<td>(33.4)</td>
<td>(6.67)</td>
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<tr>
<td>410 [L/min]</td>
<td>533</td>
<td>42</td>
<td>354</td>
<td>285</td>
<td>889</td>
</tr>
<tr>
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<td>(5.48)</td>
<td>(21.2)</td>
<td>(15.4)</td>
<td>(10.4)</td>
</tr>
<tr>
<td>492 [L/min]</td>
<td>603</td>
<td>54.3</td>
<td>358</td>
<td>332</td>
<td>858</td>
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<td>(3.01)</td>
<td>(11.8)</td>
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<tr>
<td>574 [L/min]</td>
<td>671</td>
<td>44</td>
<td>366</td>
<td>300</td>
<td>855</td>
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<td>(3.61)</td>
<td>(8.89)</td>
<td>(30.9)</td>
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<td>66.5</td>
<td>363</td>
<td>315</td>
<td>535</td>
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<tr>
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<td>(51.7)</td>
<td>(12.9)</td>
<td>(11.8)</td>
<td>(39.1)</td>
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Table L.19: Temperature data for primary air and secondary air
### Fuel Size

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<th>Fuel Size</th>
<th>Initial $T_P$</th>
<th>Time of peak [s]</th>
<th>Min $T_S$</th>
<th>Time of min $T_S$ [s]</th>
<th>Max $T_C$</th>
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<tbody>
<tr>
<td>0.15 [mm/mm]</td>
<td>517</td>
<td>57.7</td>
<td>382</td>
<td>230</td>
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<td>(18.2)</td>
<td>(11.7)</td>
<td>(25.7)</td>
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</tr>
<tr>
<td>0.19 [mm/mm]</td>
<td>618</td>
<td>83</td>
<td>445</td>
<td>228</td>
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<td>(18.7)</td>
<td>(31.8)</td>
<td>(49)</td>
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<td>0.22 [mm/mm]</td>
<td>679</td>
<td>142</td>
<td>433</td>
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### Separation Distance

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<th>Initial $T_P$</th>
<th>Time of peak [s]</th>
<th>Min $T_S$</th>
<th>Time of min $T_S$ [s]</th>
<th>Max $T_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 [mm]</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>793</td>
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<tr>
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<td>—</td>
<td>—</td>
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<td>170 [mm]</td>
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<td>—</td>
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<td>—</td>
<td>787</td>
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<td>—</td>
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<td>270 [mm]</td>
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<td>—</td>
<td>777</td>
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<td>—</td>
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<td>370 [mm]</td>
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<td>—</td>
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<td>—</td>
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Table L.20: Temperature data for fuel size and separation distance
# Water Boiling Tests

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<th>Primary Air</th>
<th>78 [L/min]</th>
<th>98 [L/min]</th>
<th>118 [L/min]</th>
<th>137 [L/min]</th>
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<tbody>
<tr>
<td>Max $T_W$</td>
<td>87</td>
<td>100</td>
<td>101</td>
<td>101</td>
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<tr>
<td>Time of max $T_W$</td>
<td>428</td>
<td>285</td>
<td>246</td>
<td>202</td>
</tr>
<tr>
<td>Average heating $[\degree C]$</td>
<td>0.152</td>
<td>0.287</td>
<td>0.335</td>
<td>0.408</td>
</tr>
<tr>
<td>Initial $T_W$</td>
<td>22</td>
<td>18.8</td>
<td>18.7</td>
<td>19.4</td>
</tr>
<tr>
<td>Heat transfer $[kJ]$</td>
<td>452</td>
<td>616</td>
<td>669</td>
<td>690</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Secondary Air</th>
<th>328 [L/min]</th>
<th>410 [L/min]</th>
<th>492 [L/min]</th>
<th>574 [L/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max $T_W$</td>
<td>87</td>
<td>100</td>
<td>101</td>
<td>101</td>
</tr>
<tr>
<td>Time of max $T_W$</td>
<td>428</td>
<td>285</td>
<td>246</td>
<td>202</td>
</tr>
<tr>
<td>Average heating $[\degree C]$</td>
<td>0.152</td>
<td>0.287</td>
<td>0.335</td>
<td>0.408</td>
</tr>
<tr>
<td>Initial $T_W$</td>
<td>22</td>
<td>18.8</td>
<td>18.7</td>
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<tr>
<td>Heat transfer $[kJ]$</td>
<td>452</td>
<td>616</td>
<td>669</td>
<td>690</td>
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Table L.21: Water boiling test data for primary air and secondary air
### Table L.22: Water boiling test data for fuel size and benchmarking

<table>
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<tr>
<th>Fuel Size</th>
<th>Max $T_W$ $[^\circ{C}]$</th>
<th>Time of max $T_W$ $[s]$</th>
<th>Average Heating Rate $[^\circ{C}/s]$</th>
<th>Initial $T_W$ $[^\circ{C}]$</th>
<th>Heat Transfer $[kJ]$</th>
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<tr>
<td>0.15 [mm/mm]</td>
<td>76.6</td>
<td>258</td>
<td>0.229</td>
<td>17.9</td>
<td>347</td>
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<td>(0.0252)</td>
<td>(1.46)</td>
<td>(18)</td>
</tr>
<tr>
<td>0.19 [mm/mm]</td>
<td>85.3</td>
<td>280</td>
<td>0.229</td>
<td>21.5</td>
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<td>(0.0193)</td>
<td>(2.32)</td>
<td>(57.5)</td>
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<td>0.22 [mm/mm]</td>
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Table L.22: Water boiling test data for fuel size and benchmarking
Appendix M

SOPs, Risk Assessments, and MSDS

1. Benchmarking SOP
2. Optimisation SOP
3. Fuel collection and preparation SOP
4. Dryer RMSS
5. Furnace RMSS
6. Manifold RMSS
7. Cow dung MSDS
SAFE OPERATING PROCEDURE:
TLUD FURNACE BENCHMARKING

LOCATION DETAILS
School/Branch: Mechanical Engineering

TASK/ACTIVITY
Operation of the TLUD Furnace – Benchmarking  
Date: 27/03/2014

PREPARED BY
<table>
<thead>
<tr>
<th>Name</th>
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<th>Signature</th>
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<tbody>
<tr>
<td>Aleksis Xenophon</td>
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<td></td>
</tr>
<tr>
<td>Oliver Robson</td>
<td>Student</td>
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<tr>
<td>James Metcalfe</td>
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</tr>
<tr>
<td>Paul Medwell</td>
<td>Supervisor</td>
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</tr>
<tr>
<td>Marc Simpson</td>
<td>Workshop Manager</td>
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HAZARD IDENTIFICATION
Risk Assessment Dated: 23 / 05 / 2013
Assessment Record  721

RISK RATING
Medium (20)

SAFE OPERATING PROCEDURE DETAILS

**STOP**

**DO NOT OPERATE PLANT** IF YOU HAVE NOT COMPLETED (1) THE COMPULSORY UNIVERSITY OF ADELAIDE OCCUPATIONAL HEALTH AND SAFETY INDUCTION COURSE, AND; (2) DO NOT POSSESS THE REQUISITE QUALIFICATIONS OR TRAINING FOR THIS PIECE OF PLANT.

Preparation – Work Area Check
- Ready access to and egress from furnace (min of 600mm clearance required)
- Area is free from grease, oil, debris and objects, which can be tripped over.  
  (Use diatomaceous earth ("kitty litter") or absorption pillow to soak up grease, coolant, oil and other fluids)
- Ready access to fire extinguisher.
- Extractor hood in working condition.

Personal Attire & Safety Equipment:
- Approved closed toe type shoes must be worn at all times.
- Approved safety spectacles/goggles must be worn at all times.
- Overalls to be worn if operating the furnace
- Long hair must be confined close to the head by an appropriate restraint.
- Thermal gloves should be worn when appropriate
SAFE OPERATING PROCEDURE: TLUD FURNACE BENCHMARKING

Machine Pre-operational Safety Checks – Safety Precautions that MUST be Observed:

- Visual inspection of machine to verify it is in good operational order, ensuring no damage to any stationary or moving parts, electrical cords etc. Any unsafe equipment is to be reported to an authorised staff member and tagged out.
- All electrical devices to be safety tagged.
- Ensure all piping and valves are adequately sealed.
- Ensure lighting and power are switched on their respective main switches, where required.  
- Be aware of other activities happening in the immediate area.
- Wear appropriate PPE.

Operation: BENCHMARKING

Furnace Preparation

- Ensure light and power is switched on at their respective switches.
- Ensure functionality of the extractor hood.
- Ensure furnace is clean and free from contamination, and the workspace is clear.
- Ensure required fuels, a stop watch or other timing mechanism, fire extinguisher and TESTO gas analyser are readily accessible.
- Select height for the fuel grating.

Benchmarking

- Place prepared fuel uniformly on the grate.
- A set quantity of igniter fluid may be added to the fuel to assist with combustion.
- Set the TESTO gas analyser at a consistent height above the furnace. Be aware of the elevated temperatures expected to be observed at this location.
- Activate the extractor hood to its minimal setting.
- Activate the gas analyser to measure emissions from the fuel.
- Ignite the fuel remotely. Eg. Dropping lit paper towel into the furnace.
- Visually ensure that combustion is occurring over entirety of the fuel source, using a mirror.
- Allow the fuel to burn to completion. If the flame must be doused before complete combustion, use water or a snuff bucket. Should the flame continue to burn in an unsafe manner, use the fire extinguisher. Record the time at this point.
- Allow a period of at least a minute for the furnace temperature to recede.
- Collect the biochar that is produced during the combustion. Storing it appropriately.

Clean Up

- Shut down the extractor hood.
- Clean the furnace combustion chamber using water. Ensure to remove any traces of contamination that may interfere with future testing.
- Clean up surrounding area.

General Safety

- NEVER LEAVE THE TLUD FURNACE OPERATING WHILST UNATTENDED.
- Visual inspection of equipment prior to use. Unsafe equipment to be tagged out and reported to Workshop Manager.
- Only authorised qualified staff may operate this furnace, or students who have received full Competency Training from an authorised qualified staff member (recorded in training register).
- PPE to be worn at all times including: safety goggles, closed toe shoes, and overalls.
- Thermal gloves to be worn when necessary.
- Long hair to be tied back.

WARNING: Information regarding the safe use of this equipment is to the best understanding at time of publication.

Effective Date: 27/03/2014  
Review Date: 27/03/2015  
Page 2 of 3
Douse flame using the snuff bucket or water before leaving it unattended.

NOTE: This Safe Operating Procedure must be reviewed within 1 year of date of issue or:
   a. After any accident, incident or near miss;
   b. When training new staff;
   c. If adopted by new work group;
   d. If equipment, substances or processes change;
SAFE OPERATING PROCEDURE: TLUD FURNACE OPTIMISATION

LOCATION DETAILS
School/Branch: Mechanical Engineering

TASK/ACTIVITY
Operation of the TLUD Furnace – Optimisation

PREPARED BY
<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aleksis Xenophon</td>
<td>Student</td>
<td></td>
</tr>
<tr>
<td>Oliver Robson</td>
<td>Student</td>
<td></td>
</tr>
<tr>
<td>James Metcalfe</td>
<td>Student</td>
<td></td>
</tr>
<tr>
<td>Paul Medwell</td>
<td>Supervisor</td>
<td></td>
</tr>
<tr>
<td>Marc Simpson</td>
<td>Workshop Manager</td>
<td></td>
</tr>
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</table>

HAZARD IDENTIFICATION
<table>
<thead>
<tr>
<th>Equipment</th>
<th>Risk Assessment Dated</th>
<th>Assessment Record</th>
<th>Risk Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace</td>
<td>23 / 05 / 2013</td>
<td>721</td>
<td>Medium (20)</td>
</tr>
<tr>
<td>Manifold</td>
<td>09 / 05 / 2013</td>
<td>1909</td>
<td>Medium (12)</td>
</tr>
</tbody>
</table>

SAFE OPERATING PROCEDURE DETAILS

STOP

DO NOT OPERATE PLANT IF YOU HAVE NOT COMPLETED (1) THE COMPULSORY UNIVERSITY OF ADELAIDE OCCUPATIONAL HEALTH AND SAFETY INDUCTION COURSE, AND; (2) DO NOT POSSESS THE REQUISITE QUALIFICATIONS OR TRAINING FOR THIS PIECE OF PLANT.

Preparation – Work Area Check
- Ready access to and egress from furnace (min of 600mm clearance required)
- Area is free from grease, oil, debris and objects, which can be tripped over.
  - (Use diatomaceous earth (“kitty litter”) or absorption pillow to soak up grease, coolant, oil and other fluids)
- Ready access to fire extinguisher.
- Extractor hood in working condition.

Personal Attire & Safety Equipment:
- Approved closed toe type shoes must be worn at all times.
- Approved safety spectacles/goggles must be worn at all times.
- Overalls to be worn if operating the furnace
- Long hair must be confined close to the head by an appropriate restraint.
- Thermal gloves should be worn when appropriate
Machine Pre-operational Safety Checks – Safety Precautions that MUST be Observed:

- Visual inspection of machine to verify it is in good operational order, ensuring no damage to any stationary or moving parts, electrical cords etc. Any unsafe equipment is to be reported to an authorised staff member and tagged out.
- All electrical devices to be safety tagged.
- Ensure all piping and valves are adequately sealed.
- Ensure lighting and power are switched on their respective main switches, where required.
- Be aware of other activities happening in the immediate area.
- Wear appropriate PPE.

Operation: OPTIMISATION

Furnace Preparation

- Ensure light and power is switched on at their respective switches.
- Check functionality of the extractor hood.
- Ensure furnace is clean and free from contamination, and the workspace is clear.
- Fuels prepared as required
- Ensure required fuels, a stop watch or other timing mechanism, fire extinguisher and TESTO gas analyser are readily accessible
- All valves fully open and sealed correctly
- Power to primary airflow fan activated
- Temperature and airflow calibrated

Optimisation

- Select height for the fuel grating.
- Set the grating upon the bolts at the chosen setting. Ensure that remaining holes are closed with either bolts or insulating tape.
- Place prepared fuel uniformly on the grate.
- Activate the extractor hood to its minimal setting.
- Add measured amount of igniter fluid to the fuel to help with combustion.
- Activate the primary airflow to required output.
- Set the TESTO gas analyser at a consistent height above the furnace. Be aware of the elevated temperatures expected to be observed at this location
- Activate the gas analyser to measure emissions from the fuel.
- Ignite the fuel using either wooden matches or a BBQ lighter. Start the timer to determine burn time.
- Visually ensure that combustion is occurring as should be, using a mirror
- Allow the fuel to burn to completion. If the flame must be doused before complete combustion, use water or a snuff bucket. Should the flame continue to burn in an unsafe manner, use the fire extinguisher. Record the time at this point.
- Allow a period of at least a minute for the furnace temperature to recede.
- Collect the biochar that is produced during the combustion. This should then be stored in a sealed container to prevent contamination. A vacuum or similar can be used for collection.

Clean Up

- Shut off the primary airflow fans.
- Shut down the extractor hood.
- Clean the furnace combustion chamber using water. Ensure to remove any traces of contamination that may interfere with future testing.
- Clean up surrounding area.
## General Safety

- NEVER LEAVE THE TLUD FURNACE OPERATING WHILST UNATTENDED.
- Visual inspection of equipment prior to use. Unsafe equipment to be tagged out and reported to Workshop Manager.
- Only authorised qualified staff may operate this furnace, or students who have received full Competency Training from an authorised qualified staff member (recorded in training register).
- PPE to be worn at all times including: safety goggles, closed toe shoes, and overalls.
- Thermal gloves to be worn when necessary
- Long hair to be tied back.
- Douse flame using the snuff bucket or water before leaving it unattended.

**NOTE:** This Safe Operating Procedure must be reviewed within 1 year of date of issue or:
- After any accident, incident or near miss;
- When training new staff;
- If adopted by new work group;
- If equipment, substances or processes change;
SAFE OPERATING PROCEDURE: FUEL COLLECTION AND PREPARATION

LOCATION DETAILS
School/Branch: Mechanical Engineering

TASK/ACTIVITY
Fuel Collection and Preparation

DATE: 12/08/13

PREPARED BY

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SAFE OPERATING PROCEDURE DETAILS

STOP

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Preparation – Work Area Check
- Area is free from grease, oil, debris and objects, which can be tripped over.
- Area is clear of unauthorised people before commencing work.

Personal Attire & Safety Equipment:
- Approved closed toe type shoes must be worn at all times.
- Approved safety spectacles/goggles must be worn at all times.
- Long hair must be confined close to the head by an appropriate restraint.
- Finger rings and exposed loose jewellery (eg bracelets and necklaces) must not be worn. Medic Alert bracelet must be taped if exposed.
- Gloves must be worn at all times.
- Surgical mask may also be required

Pre-operational Safety Checks – Safety Precautions that MUST be observed:
- Ensure storage and shovelling capabilities are adequate
- Be aware of other activities happening in the immediate area.
- Ensure that no slip and/or trip hazards are present.
- Ensure that lighting is adequate.
- Wear appropriate PPE for task being performed (i.e. safety glasses. Gloves required when cleaning).
- Ensure proper shovelling technique is known to the operator
- Ensure all quarantine regulations are met for animal waste.
- Ensure all solid fuels are approved and safe for collection.

WARNING: Information regarding the safe use of this equipment is to the best understanding at time of publication.
Proper storage facilities (i.e. containers) are approved and maintained.

**Operation**

**Collection**
- Shovel the dung into a container. Correct shovelling technique should be maintained to reduce the risk of injury.
- Ensure that the container is free from damage and seal adequately.

**Washing**
- Ensure washing of dung are conducted at a safe and approved location to prevent contamination to the surroundings.
- Proper channelling of the waste and disposal of residues should be approved by the person in-charge on site.
- Load the dung into a colander or similar device.
- Fill the cylinder with water so as to clean the fuel.
- Add in a known ratio of mixing material if desired.
- Allow the fuel to dry.

**Forming**
- Ensure properly ventilated area to prevent inhaling in harmful gases.
- Use a melon baller or similar to obtain required size
- Place fuels into tubes and compact into cake size
- Place onto racks for drying

**Furnace Drying**
- Transfer all dry materials outside and way from other people
- Place cakes onto furnace drying trays
- Place into furnace
- Set furnace to desired temperature
- Inform Lab Manager when the furnace is being switched on
- Turn on
- When removing trays, allow trays to cool and wear appropriate PPE

**Storage**
- Ensure there is a designated storage location that is available for the containers of fuels. This location should be away from common thoroughfares and safely secured.

**General Safety**
- PPE to be worn at all times
- Long hair to be tied back.
- Be aware of surrounding objects and people
- Use correct lifting technique (knees)

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  a. After any accident, incident or near miss;
  b. When training new staff;
  c. If adopted by new work group;
  d. If equipment, substances or processes change;

**WARNING**: Information regarding the safe use of this equipment is to the best understanding at time of publication.
## Risk Register

**Location**: The University of Adelaide - Fac of Eng, Comp & Math Sci - School of Mechanical Eng - N/A - Thebarton - The Factory 10/Store House 11 - FAC - FAC - Level G - Workshop - 1389: Cookstove Fuel Prep

**Assessment Category**: Plant - General

**Assessment Type**: Plant & Equipment

**Master Category**: OHS

<table>
<thead>
<tr>
<th>Location</th>
<th>Faculty/ Division</th>
<th>Discipline/ Unit</th>
<th>Building</th>
<th>Room Type</th>
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<tbody>
<tr>
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<td>Fac of Eng, Comp &amp; Math Sci</td>
<td>*N/A</td>
<td>The Factory 10/Store House 11 - FAC</td>
<td>Workshop</td>
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<tr>
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<th>School/ Branch</th>
<th>Campus</th>
<th>Room</th>
<th>Item / Activity</th>
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<tbody>
<tr>
<td>The University of Adelaide</td>
<td>School of Mechanical Eng</td>
<td>Thebarton</td>
<td>FAC - Level G</td>
<td>1389: Cookstove Fuel Prep</td>
</tr>
</tbody>
</table>

**Assessment Record**: 1979

**Assessment Checklist**: OHS - Plant - General

### Assessment Details

#### Hazard: * Contact with hot object or friction burn

- **Hazard Description/Nature of Risk**: Is there the potential for a person to come into contact with an object which is hotter than 50 degrees Celsius? Eg steam, naked flame, laser beams

- **How can this hazard/threat cause an incident/adverse event?**
  The furnace will be run at temperature around 50C which could cause a burn if inappropriately handled.

- **Residual Risk**
  - Medium (10)

- **Assessor**: Andrew Crowe

- **Risk Assessment Keywords**
  - burn, heat, thermal gloves

<table>
<thead>
<tr>
<th>Actions Description</th>
<th>Control Statement</th>
<th>Responsible Person</th>
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#### Hazard: * Contact with electricity or potential for electric shock

- **Hazard Description/Nature of Risk**: Is there the potential for a person to come into contact with live electricity or receive an electric shock? Eg Overhead or underground power lines, exposed wires, water near equipment, leads/switch in poor condition

- **How can this hazard/threat cause an incident/adverse event?**
  The drying furnace runs on electricity so faulty wiring or a short could cause damage to the operator and/or the surroundings

- **Residual Risk**
  - Low (6)

- **Assessor**: Andrew Crowe

- **Risk Assessment Keywords**
  - electricity, furnace, drier

<table>
<thead>
<tr>
<th>Actions Description</th>
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<tr>
<td>Hazard</td>
<td>Hazard Description/Nature of Risk</td>
<td>How can this hazard/threat cause an incident/adverse event?</td>
<td>Residual</td>
<td>Assessor</td>
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<tr>
<td>* Contact with stationary object</td>
<td>Is there the potential for a person to run or bump into a stationary object? Eg knock their hand on a wall when an object</td>
<td>The furnace is large and bulky and the room it is enclosed in has many shelves and storage boxes. Tripping on these could cause the operator to fall into other objects, possibly damaging them and the operator</td>
<td>Low (4)</td>
<td>Andrew Crowe</td>
<td></td>
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</tbody>
</table>

**What controls are currently in place?**
Walkway is kept clear of loose objects. Minimise the number of operators present to acceptable levels.

<table>
<thead>
<tr>
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<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Exposure to biological hazards</td>
<td>Is there the potential for a person to be exposed to biological hazards?</td>
<td>The fuel to be dried is of a biological nature and can emit smells and hazards which could affect the operators health.</td>
<td>Low (4)</td>
<td>Andrew Crowe</td>
</tr>
</tbody>
</table>

**What controls are currently in place?**
Fuel is cleaned and washed before use, Area is well ventilated

<table>
<thead>
<tr>
<th>Actions Description</th>
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</table>
## Risk Register

**Location** The University of Adelaide - Fac of Eng, Comp & Math Sci - School of Mechanical Eng - Thebarton - The Factory 10/Store House 11 - FAC - *Level G - Lab - Burner / Flame testing

**Assessment Category** Tasks - General

**Master Category** OHS

<table>
<thead>
<tr>
<th><strong>Tasks</strong></th>
<th><strong>Assessment Type</strong></th>
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<tr>
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<tr>
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<td>Item / Activity</td>
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</table>

**Assessment Record:** 721  
**Assessment Checklist:** OHS - Tasks - General

### Hazard

**Hazard Description/Nature of Risk**

- *** Explosion / Fire hazards**
  - Is there a potential for a person to be injured by an explosion or fire? e.g. ignition of surrounding area, using naked flame, gas, vapour, grain silos, chemical incompatibility, shock sensitive chemicals, chemical stability

**How can this hazard/threat cause an incident/adverse event?**

- Gas leak from burner or transfer hoses.

**Residual Risk**

- Medium (20)

**Assessor**

- Richard Craig (Mech Eng)

**Risk Assessment Keywords**

- Gas leak

### What controls are currently in place?

- SOP requires operator to check for leaks within system before flame operation.
- SOP requires operator to be near fuel isolation valve at all times.
- Ensure access to fire extinguishers and blankets.
- Ensure access to emergency services.

<table>
<thead>
<tr>
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</tr>
</thead>
</table>

### Hazard

**Hazard Description/Nature of Risk**

- *** Exposure to gas (asphyxiants)**
  - Is there the potential for a person to be exposed to gas causing oxygen displacement? e.g. diesel emissions, liquid N, dry ice

**How can this hazard/threat cause an incident/adverse event?**

- Irritation or damage to the respiratory system of the operator

**Residual Risk**

- Medium (12)

**Assessor**

- Andrew Crowe

**Risk Assessment Keywords**

- Breathing, gas, fumes, smoke, pollutants, particulates, air

### What controls are currently in place?

- Extractor hood, well ventilated area

<table>
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<tr>
<th>Actions Description</th>
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<tr>
<td>Hazard</td>
<td>Hazard Description/Nature of Risk</td>
<td>How can this hazard/threat cause an incident/adverse event?</td>
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</tr>
<tr>
<td>* Contact with hot object or friction burn</td>
<td>Is there the potential for a person to come into contact with an object which is hotter than 50 degrees Celsius? e.g. steam, naked flame, laser beams, heating block</td>
<td>Burn from hot burner nozzles. Burn from naked flame.</td>
<td>Medium (10)</td>
<td>Richard Craig (Mech Eng)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**What controls are currently in place?**

SOP describes continued use of cooling air after experiment to cool heated components. SOP instructs operators to stand away from the burner before and after flame ignition. Ensure access to cool running water for first aid treatment of burns.

**Risk Assessment Keywords**

- skin burn

<table>
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<tbody>
<tr>
<td>* Contact with chemicals, fumes or gas</td>
<td>Is there the potential for a person to come into contact with chemicals or gas? e.g. fumes from chemicals, dry ice, machine oils, Liquid N2</td>
<td>Cause irritation to the naked body and burns over exposed area, respiratory problems</td>
<td>Medium (10)</td>
<td>Andrew Crowe</td>
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</tbody>
</table>

**What controls are currently in place?**

Extractor hood, safety goggles, ventilated area.

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<td>Is there the potential for a person to come into contact with an object which is hotter than 50 degrees Celsius? e.g. steam, naked flame, laser beams, heating block</td>
<td>Severe burns over exposed areas on the body.</td>
<td>Medium (10)</td>
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**What controls are currently in place?**

Safety Gloves, Coveralls, Safety goggles

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<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Contact with stationary object</td>
<td>Is there the potential for a person to run or bump into a stationary object? e.g. knock their hand on a wall when pushing a trolley</td>
<td>Severe injuriesAdequate lighting, safety tape on the ground</td>
<td>Medium (10)</td>
<td>Andrew Crowe</td>
</tr>
</tbody>
</table>

**What controls are currently in place?**

Adequate lighting, safety tape on the ground

<table>
<thead>
<tr>
<th>Actions Description</th>
<th>Control Statement</th>
<th>Responsible Person</th>
<th>Due Date</th>
<th>Cost</th>
<th>Progress/Notes</th>
<th>Control Type</th>
</tr>
</thead>
</table>
### Actions Description

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Cost</th>
<th>Progress/Notes</th>
<th>Control Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Explosion / Fire hazards</td>
<td>Is there a potential for a person to be injured by an explosion or fire? e.g. ignition of surrounding area, using naked flame, gas, vapour, grain silos, chemical incompatibility, shock sensitive chemicals, chemical stability</td>
<td>severe burns</td>
<td>Medium (10)</td>
<td>Andrew Crowe</td>
<td>Residual</td>
</tr>
</tbody>
</table>

### What controls are currently in place?

- Well ventilated areas, extractor hood, fire extinguishers within reach
- Fire, explosion

### Actions Description

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Cost</th>
<th>Progress/Notes</th>
<th>Control Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Exposure to biological hazards</td>
<td>Is there the potential for a person to be exposed to biological hazards? e.g. human or animal body fluids, infectious waste, cultures of micro-organisms</td>
<td>irritation on skin or body parts</td>
<td>Medium (10)</td>
<td>Andrew Crowe</td>
<td>Residual</td>
</tr>
</tbody>
</table>

### What controls are currently in place?

- Safety gloves, Safety goggles, Adequate clothing
- Animal dung, bio waste

### Actions Description

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Cost</th>
<th>Progress/Notes</th>
<th>Control Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Other</td>
<td>Are there any other hazards associated with this item/activity?</td>
<td>Burner tipping over : causes burns or fire within laboratory.</td>
<td>Low (6)</td>
<td>Richard Craig (Mech Eng)</td>
<td>Residual</td>
</tr>
</tbody>
</table>

### What controls are currently in place?

- SOP requires operator to be near fuel isolation valve at all times.
- Burner fixed to ground using heavy weights or bolts.

### Actions Description

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Cost</th>
<th>Progress/Notes</th>
<th>Control Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Exposure to hot environment</td>
<td>Is there the potential for a person to be exposed to hot or humid environments? e.g. harvesting, remote areas</td>
<td>Heat stress or dehydration from extended exposure to flame</td>
<td>Low (4)</td>
<td>Richard Craig (Mech Eng)</td>
<td>Residual</td>
</tr>
</tbody>
</table>

### What controls are currently in place?

- SOP instructs operators to stand away from the flame during operation.
- All experiments are of short duration to reduce exposure time.
SOP instructs operators to stand away from the flame during operation. All experiments are of short duration to reduce exposure time.

<table>
<thead>
<tr>
<th>Actions Description</th>
<th>Control Statement</th>
<th>Responsible Person</th>
<th>Due Date</th>
<th>Cost Progress/Notes</th>
<th>Control Type</th>
</tr>
</thead>
</table>

### Hazard Description/Nature of Risk

**Hazard**

* Slips, trips or falls
  - Is there the potential for a person to slip, trip or fall? e.g. slippery, uneven or cluttered work surfaces, plant location, lack of safe guards such as rails

### How can this hazard/threat cause an incident/adverse event?

- tripping over fuel / air supply piping/hoses

### Residual Risk Assessment Keywords

- tripping over hoses

### What controls are currently in place?

- Use overhead piping system where appropriate.
- Place visible covers over piping / hoses.
- Route pipes/hoses away from test area and walkway.

### Action Description

<table>
<thead>
<tr>
<th>Actions Description</th>
<th>Control Statement</th>
<th>Responsible Person</th>
<th>Due Date</th>
<th>Cost Progress/Notes</th>
<th>Control Type</th>
</tr>
</thead>
</table>

### Hazard Description/Nature of Risk

**Hazard**

* Contact with sharp object
  - Is there the potential for a person to be cut, stabbed or punctured by a sharp object? e.g. knife, sharp or pointy edge objects, flying or moving objects

### How can this hazard/threat cause an incident/adverse event?

- Cuts on exposed areas on the body.

### Residual Risk Assessment Keywords

- Sharp, cut, burrs

### What controls are currently in place?

- Safety Gloves, Safety Goggles

### Action Description

<table>
<thead>
<tr>
<th>Actions Description</th>
<th>Control Statement</th>
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<th>Due Date</th>
<th>Cost Progress/Notes</th>
<th>Control Type</th>
</tr>
</thead>
</table>

### Hazard Description/Nature of Risk

**Hazard**

* Environmental hazards
  - Is there a possibility of generating significant environmental hazards? e.g. energy/water consumption, hazardous waste/emissions

### How can this hazard/threat cause an incident/adverse event?

- possible cause for poisoning due to contact or inhaling gas/waste emissions.

### Residual Risk Assessment Keywords

- animal dung, biological waste, gas emissions, smoke, air pollution

### What controls are currently in place?

- extractor hood, well ventilated areas, first aid kits.
<table>
<thead>
<tr>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Overstress - manual handling and ergonomics</td>
<td>Is there the potential for a person to be exposed to manual handling injury through reaching, bending, twisting, lifting, pulling, pushing or repetitive motions?</td>
<td>Severe strain on body, body sprain.</td>
<td>Low (4)</td>
<td>Andrew Crowe</td>
</tr>
</tbody>
</table>

What controls are currently in place?
- having enough rest, Keeping hydrated and eating enough food. Alternate heavy lifting duties

Risk Assessment Keywords
- lifting, heavy, weight, mass

<table>
<thead>
<tr>
<th>Actions Description</th>
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<th>Progress/Notes</th>
<th>Control Type</th>
</tr>
</thead>
</table>

Generated on Thursday, May 23, 2013 10:03:52 PM
## Risk Register

**Location**  The University of Adelaide - Fac of Eng, Comp & Math Sci - School of Mechanical Eng - *N/A - Thebarton - Laboratories Building - TLB - *Level G - Workshop - 1389 - Cookstove air connector

**Entity**  The University of Adelaide

**School/Branch**  School of Mechanical Eng

**Campus**  Thebarton

**Building**  *Level G*

**Room**  Workshop

**Room Type**  1389 - Cookstove air connector

**Assessment Category**  Plant - General

**Assessment Type**  Plant & Equipment

**Master Category**  OHS

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Hazard Description/Nature of Risk</th>
<th>How can this hazard/threat cause an incident/adverse event?</th>
<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Contact with electricity or potential for electric shock</td>
<td>Is there the potential for a person to come into contact with live electricity or receive an electric shock? Eg Overhead or underground power lines, exposed wires, water near equipment, leads/switch in poor condition</td>
<td>Heat guns used may malfunction or interact with hot manifolds/cookstove reactor causing damage and exposure of electrical wires. This also applies to the centrifugal fan which runs off mains power.</td>
<td>Medium (12)</td>
<td>Andrew Crowe</td>
</tr>
</tbody>
</table>

**Risk Assessment Keywords**
- electricity, heat guns, fan

**What controls are currently in place?**
- Electrical testing of equipment, management of wire positioning to decrease risk of interaction with hot equipment

<table>
<thead>
<tr>
<th>Actions Description</th>
<th>Control Statement</th>
<th>Responsible Person</th>
<th>Due Date</th>
<th>Cost</th>
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</table>

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<tr>
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<th>Residual</th>
<th>Assessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Contact with hot object or friction burn</td>
<td>Is there the potential for a person to come into contact with an object which is hotter than 50 degrees Celsius? Eg steam, naked flame, laser beams</td>
<td>Air manifold is heated up by heat guns and if touched may cause burns</td>
<td>Medium (10)</td>
<td>Andrew Crowe</td>
</tr>
</tbody>
</table>

**Risk Assessment Keywords**
- PPE equipment required to be worn around the manifold, signs/indicators to show that surface is hot
- hot surface, heat

<table>
<thead>
<tr>
<th>Actions Description</th>
<th>Control Statement</th>
<th>Responsible Person</th>
<th>Due Date</th>
<th>Cost</th>
<th>Progress/Notes</th>
<th>Control Type</th>
</tr>
</thead>
</table>
**Brunnings Cow Manure**

**Brunnings Garden Products**

**Chemwatch: 7104-61**  
**Version No: 4.1.1.1**  
Safety Data Sheet according to WHS and ADG requirements

---

## SECTION 1 IDENTIFICATION OF THE SUBSTANCE / MIXTURE AND OF THE COMPANY / UNDERTAKING

### Product Identifier

<table>
<thead>
<tr>
<th><strong>Product name</strong></th>
<th>Brunnings Cow Manure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical Name</strong></td>
<td>Not Applicable</td>
</tr>
<tr>
<td><strong>Synonyms</strong></td>
<td>manure, soil conditioner</td>
</tr>
<tr>
<td><strong>Proper shipping name</strong></td>
<td>Not Applicable</td>
</tr>
<tr>
<td><strong>Chemical formula</strong></td>
<td>Not Applicable</td>
</tr>
<tr>
<td><strong>Other means of identification</strong></td>
<td>Not Available</td>
</tr>
<tr>
<td><strong>CAS number</strong></td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>

### Relevant identified uses of the substance or mixture and uses advised against

| **Relevant identified uses** | Soil conditioner. |

### Details of the supplier of the safety data sheet

<table>
<thead>
<tr>
<th><strong>Registered company name</strong></th>
<th>Brunnings Garden Products</th>
</tr>
</thead>
</table>
| **Address**                 | Unit 3, 19-23 Clarinda Road  
Oakleigh South 3167 VIC Australia |
| **Telephone**               | +61 3 9543 5600            |
| **Fax**                     | +61 3 9543 5300            |
| **Website**                 | Not Available             |
| **Email**                   | Not Available             |

### Emergency telephone number

<table>
<thead>
<tr>
<th><strong>Association / Organisation</strong></th>
<th>Not Available</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emergency telephone numbers</strong></td>
<td>Not Available</td>
</tr>
<tr>
<td><strong>Other emergency telephone numbers</strong></td>
<td>Not Available</td>
</tr>
</tbody>
</table>

---

## SECTION 2 HAZARDS IDENTIFICATION

### Classification of the substance or mixture

HAZARDOUS CHEMICAL. NON-DANGEROUS GOODS. According to the Model WHS Regulations and the ADG Code.

**CHEMWATCH HAZARD RATINGS**

<table>
<thead>
<tr>
<th><strong>Rating</strong></th>
<th><strong>Min</strong></th>
<th><strong>Max</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flammability</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Toxicity</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Body Contact</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Reactivity</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Reactivity</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

**Poisons Schedule**  
Not Applicable

**GHS Classification [1]**  
Respiratory Sensitizer Category 1, Skin Sensitizer Category 1, STOT - SE (Resp. Irr.) Category 3*  
*LIMITED EVIDENCE

**Legend:**  

---

Continued...
Label elements

GHS label elements

SIGNAL WORD  DANGER

Hazard statement(s)

<table>
<thead>
<tr>
<th>Hazard Statement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H334</td>
<td>May cause allergy or asthma symptoms or breathing difficulties if inhaled</td>
</tr>
<tr>
<td>H317</td>
<td>May cause an allergic skin reaction</td>
</tr>
<tr>
<td>H335</td>
<td>May cause respiratory irritation*</td>
</tr>
</tbody>
</table>

*LIMITED EVIDENCE

Precautionary statement(s): Prevention

<table>
<thead>
<tr>
<th>Precautionary Statement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P261</td>
<td>Avoid breathing dust/fume/gas/mist/vapours/spray.</td>
</tr>
<tr>
<td>P271</td>
<td>Use only outdoors or in a well-ventilated area.</td>
</tr>
<tr>
<td>P280</td>
<td>Wear protective gloves/protective clothing/eye protection/face protection.</td>
</tr>
<tr>
<td>P284</td>
<td>[In case of inadequate ventilation] wear respiratory protection.</td>
</tr>
<tr>
<td>P272</td>
<td>Contaminated work clothing should not be allowed out of the workplace.</td>
</tr>
</tbody>
</table>

Precautionary statement(s): Response

<table>
<thead>
<tr>
<th>Precautionary Statement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P304+P340</td>
<td>IF INHALED: Remove person to fresh air and keep comfortable for breathing.</td>
</tr>
<tr>
<td>P321</td>
<td>Specific treatment (see advice on this label).</td>
</tr>
<tr>
<td>P342+P311</td>
<td>If experiencing respiratory symptoms: Call a POISON CENTER/doctor/physician/first aider</td>
</tr>
<tr>
<td>P302+P352</td>
<td>IF ON SKIN: Wash with plenty of water and soap</td>
</tr>
<tr>
<td>P312</td>
<td>Call a POISON CENTER/doctor/physician/first aider/if you feel unwell.</td>
</tr>
<tr>
<td>P333+P313</td>
<td>If skin irritation or rash occurs: Get medical advice/attention.</td>
</tr>
<tr>
<td>P362+P364</td>
<td>Take off contaminated clothing and wash it before reuse.</td>
</tr>
</tbody>
</table>

Precautionary statement(s): Storage

<table>
<thead>
<tr>
<th>Precautionary Statement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P405</td>
<td>Store locked up.</td>
</tr>
<tr>
<td>P403+P233</td>
<td>Store in a well-ventilated place. Keep container tightly closed.</td>
</tr>
</tbody>
</table>

Precautionary statement(s): Disposal

<table>
<thead>
<tr>
<th>Precautionary Statement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P501</td>
<td>Dispose of contents/container to authorised chemical landfill or if organic to high temperature incineration</td>
</tr>
</tbody>
</table>

SECTION 3 COMPOSITION / INFORMATION ON INGREDIENTS

Substances

See section below for composition of Mixtures

Mixtures

<table>
<thead>
<tr>
<th>CAS No</th>
<th>%[weight]</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>NotSpec.</td>
<td></td>
<td>bacteria</td>
</tr>
<tr>
<td>NotSpec.</td>
<td></td>
<td>compost</td>
</tr>
<tr>
<td>NotSpec.</td>
<td></td>
<td>fungi</td>
</tr>
<tr>
<td>NotSpec.</td>
<td></td>
<td>manure</td>
</tr>
<tr>
<td>NotSpec.</td>
<td></td>
<td>mulch</td>
</tr>
<tr>
<td>NotSpec.</td>
<td></td>
<td>organic compounds</td>
</tr>
<tr>
<td>NotSpec.</td>
<td></td>
<td>protozoa</td>
</tr>
<tr>
<td>14808-60-7.</td>
<td>NotSpec.</td>
<td>graded sand</td>
</tr>
</tbody>
</table>
SECTION 4 FIRST AID MEASURES

Description of first aid measures

Eye Contact
If this product comes in contact with the eyes:
› Wash out immediately with fresh running water.
› Ensure complete irrigation of the eye by keeping eyelids apart and away from eye and moving the eyelids by occasionally lifting the upper and lower lids.
› Seek medical attention without delay; if pain persists or recurs seek medical attention.
› Removal of contact lenses after an eye injury should only be undertaken by skilled personnel.

Skin Contact
If skin contact occurs:
› Immediately remove all contaminated clothing, including footwear.
› Flush skin and hair with running water (and soap if available).
› Seek medical attention in event of irritation.

Inhalation
› If fumes, aerosols or combustion products are inhaled remove from contaminated area.
› Other measures are usually unnecessary.

Ingestion
› If swallowed do NOT induce vomiting.
› If vomiting occurs, lean patient forward or place on left side (head-down position, if possible) to maintain open airway and prevent aspiration.
› Observe the patient carefully.
› Never give liquid to a person showing signs of being sleepy or with reduced awareness; i.e. becoming unconscious.
› Give water to rinse out mouth, then provide liquid slowly and as much as casualty can comfortably drink.
› Seek medical advice.

Indication of any immediate medical attention and special treatment needed
Treat symptomatically.

SECTION 5 FIREFIGHTING MEASURES

Extinguishing media
› There is no restriction on the type of extinguisher which may be used.
› Use extinguishing media suitable for surrounding area.

Special hazards arising from the substrate or mixture
Fire Incompatibility
› Avoid contamination with oxidising agents i.e. nitrates, oxidising acids, chlorine bleaches, pool chlorine etc. as ignition may result

Advice for firefighters
Fire Fighting
› Alert Fire Brigade and tell them location and nature of hazard.
› Wear breathing apparatus plus protective gloves in the event of a fire.
› Prevent, by any means available, spillage from entering drains or water courses.
› Use fire fighting procedures suitable for surrounding area.
› DO NOT approach containers suspected to be hot.
› Cool fire exposed containers with water spray from a protected location.
› If safe to do so, remove containers from path of fire.
› Equipment should be thoroughly decontaminated after use.

Fire/Explosion Hazard
› Non combustible.
› Not considered a significant fire risk, however containers may burn. Decomposition may produce toxic fumes of:
  › carbon monoxide (CO)
  › carbon dioxide (CO2)
  › other pyrolysis products typical of burning organic material
› May emit poisonous fumes.
› May emit corrosive fumes.

SECTION 6 ACCIDENTAL RELEASE MEASURES

Personal precautions, protective equipment and emergency procedures
Minor Spills

- Remove all ignition sources.
- Clean up all spills immediately.
- Avoid contact with skin and eyes.
- Control personal contact with the substance, by using protective equipment.
- Use dry clean up procedures and avoid generating dust.
- Place in a suitable, labelled container for waste disposal.

Major Spills

Moderate hazard.

- CAUTION: Advise personnel in area.
- Alert Emergency Services and tell them location and nature of hazard.
- Control personal contact by wearing protective clothing.
- Prevent, by any means available, spillage from entering drains or water courses.
- Recover product wherever possible.

IF DRY:
- Use dry clean up procedures and avoid generating dust. Collect residues and place in sealed plastic bags or other containers for disposal.

IF WET:
- Vacuum/shovel up and place in labelled containers for disposal.

ALWAYS:
- Wash area down with large amounts of water and prevent runoff into drains.
- If contamination of drains or waterways occurs, advise Emergency Services.

Personal Protective Equipment advice is contained in Section 8 of the MSDS.

SECTION 7 HANDLING AND STORAGE

Precautions for safe handling

- Avoid all personal contact, including inhalation.
- Wear protective clothing when risk of exposure occurs.
- Use in a well-ventilated area.
- Prevent concentration in hollows and sumps.
- DO NOT enter confined spaces until atmosphere has been checked.
- DO NOT allow material to contact humans, exposed food or food utensils.
- Avoid contact with incompatible materials.
- When handling, DO NOT eat, drink or smoke.
- Keep containers securely sealed when not in use.
- Avoid physical damage to containers.
- Always wash hands with soap and water after handling.
- Work clothes should be laundered separately. Launder contaminated clothing before re-use.
- Use good occupational work practice.
- Observe manufacturer's storage and handling recommendations contained within this MSDS.
- Atmosphere should be regularly checked against established exposure standards to ensure safe working conditions are maintained.
- Organic powders when finely divided over a range of concentrations regardless of particulate size or shape and suspended in air or some other oxidizing medium may form explosive dust-air mixtures and result in a fire or dust explosion (including secondary explosions)
- Minimise airborne dust and eliminate all ignition sources. Keep away from heat, hot surfaces, sparks, and flame.
- Establish good housekeeping practices.
- Remove dust accumulations on a regular basis by vacuuming or gentle sweeping to avoid creating dust clouds.
- Use continuous suction at points of dust generation to capture and minimise the accumulation of dusts. Particular attention should be given to overhead and hidden horizontal surfaces to minimise the probability of a "secondary" explosion. According to NFPA Standard 654, dust layers 1/32 in. (0.8 mm) thick can be sufficient to warrant immediate cleaning of the area.
- Do not use air hoses for cleaning.
- Minimise dry sweeping to avoid generation of dust clouds. Vacuum dust-accumulating surfaces and remove to a chemical disposal area. Vacuums with explosion-proof motors should be used.
- Control sources of static electricity. Dusts or their packages may accumulate static charges, and static discharge can be a source of ignition.
- Solids handling systems must be designed in accordance with applicable standards (e.g. NFPA including 654 and 77) and other national guidance.
- Do not empty directly into flammable solvents or in the presence of flammable vapors.
- The operator, the packaging container and all equipment must be grounded with electrical bonding and grounding systems. Plastic bags and plastics cannot be grounded, and antistatic bags do not completely protect against development of static charges.

Empty containers may contain residual dust which has the potential to accumulate following settling. Such dusts may explode in the presence of an appropriate ignition source.

- DO NOT cut, drill, grind or weld such containers.
- In addition ensure such activity is not performed near full, partially empty or empty containers without appropriate workplace safety authorisation or permit.
Other information

- Store in original containers.
- Keep containers securely sealed.
- Store in a cool, dry area protected from environmental extremes.
- Store away from incompatible materials and foodstuff containers.
- Protect containers against physical damage and check regularly for leaks.
- Observe manufacturer's storage and handling recommendations contained within this MSDS.

For major quantities:
- Consider storage in bunded areas - ensure storage areas are isolated from sources of community water (including stormwater, ground water, lakes and streams).
- Ensure that accidental discharge to air or water is the subject of a contingency disaster management plan; this may require consultation with local authorities.

Conditions for safe storage, including any incompatibilities

**Suitable container**
Multi-ply paper bag with sealed plastic liner or heavy gauge plastic bag.

**NOTE:** Bags should be stacked, blocked, interlocked, and limited in height so that they are stable and secure against sliding or collapse. Check that all containers are clearly labelled and free from leaks. Packing as recommended by manufacturer.

**Storage incompatibility**
- Avoid reaction with oxidising agents

| + | X | + | X | X | + |

- **X** — Must not be stored together
- **0** — May be stored together with specific precautions
- **+** — May be stored together

**PACKAGE MATERIAL INCOMPATIBILITIES**
Not Available

**SECTION 8 EXPOSURE CONTROLS / PERSONAL PROTECTION**

**Control parameters**

**OCCUPATIONAL EXPOSURE LIMITS (OEL)**

**INGREDIENT DATA**

<table>
<thead>
<tr>
<th>Source</th>
<th>Ingredient</th>
<th>Material name</th>
<th>TWA</th>
<th>STEL</th>
<th>Peak</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia Exposure Standards</td>
<td>graded sand</td>
<td>Quartz (respirable dust) / Silica - Crystalline Quartz (respirable dust)</td>
<td>0.1 (mg/m3)</td>
<td>Not Available</td>
<td>Not Available</td>
<td>(see Chapter 14) / (see Silica - Crystalline)</td>
</tr>
</tbody>
</table>

**EMERGENCY LIMITS**

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>TEEL-0</th>
<th>TEEL-1</th>
<th>TEEL-2</th>
<th>TEEL-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>graded sand</td>
<td>0.3(ppm)</td>
<td>0.3(ppm)</td>
<td>0.3(ppm)</td>
<td>50(ppm)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Original IDLH</th>
<th>Revised IDLH</th>
</tr>
</thead>
<tbody>
<tr>
<td>graded sand</td>
<td>N.E.(mg/m3) N.E.(ppm)</td>
<td>50(mgm3)</td>
</tr>
</tbody>
</table>

**MATERIAL DATA**

It is the goal of the ACGIH (and other Agencies) to recommend TLVs (or their equivalent) for all substances for which there is evidence of health effects at airborne concentrations encountered in the workplace.

At this time no TLV has been established, even though this material may produce adverse health effects (as evidenced in animal experiments or clinical experience). Airborne concentrations must be maintained as low as is practically possible and occupational exposure must be kept to a minimum.

**NOTE:** The ACGIH occupational exposure standard for Particles Not Otherwise Specified (P.N.O.S) does NOT apply.

Sensory irritants are chemicals that produce temporary and undesirable side-effects on the eyes, nose or throat. Historically occupational exposure standards for these irritants have been based on observation of workers' responses to various airborne concentrations. Present day expectations require that nearly every individual should be protected against even minor sensory irritation and exposure standards are established using uncertainty factors or safety factors of 5 to 10 or more. On occasion animal no-observable-effect-levels (NOEL) are used to determine these limits where human results are unavailable. An additional approach, typically used by the TLV committee (USA) in determining respiratory standards for this group of chemicals, has been to assign ceiling values (TLV C) to rapidly acting irritants and to assign short-term exposure limits (TLV STELs) when the weight of evidence from irritation, bioaccumulation and other endpoints combine to warrant such a limit. In contrast the MAK Commission (Germany) uses a five-category system based on...
**Exposure controls**

Engineering controls are used to remove a hazard or place a barrier between the worker and the hazard. Well-designed engineering controls can be highly effective in protecting workers and will typically be independent of worker interactions to provide this high level of protection. The basic types of engineering controls are:

- Process controls which involve changing the way a job activity or process is done to reduce the risk.
- Enclosure and/or isolation of emission source which keeps a selected hazard "physically" away from the worker and ventilation that strategically "adds" and "removes" air in the work environment. Ventilation can remove or dilute an air contaminant if designed properly. The design of a ventilation system must match the particular process and chemical or contaminant in use.
- Employers may need to use multiple types of controls to prevent employee overexposure.

Local exhaust ventilation usually required. If risk of overexposure exists, wear approved respirator. Correct fit is essential to obtain adequate protection. Supplied-air type respirator may be required in special circumstances. Correct fit is essential to ensure adequate protection.

An approved self contained breathing apparatus (SCBA) may be required in some situations.

Provide adequate ventilation in warehouse or closed storage area. Air contaminants generated in the workplace possess varying "escape" velocities which, in turn, determine the "capture velocities" of fresh circulating air required to effectively remove the contaminant.

<table>
<thead>
<tr>
<th>Type of Contaminant:</th>
<th>Air Speed:</th>
</tr>
</thead>
<tbody>
<tr>
<td>solvent, vapours, degreasing etc., evaporating from tank (in still air).</td>
<td>0.25-0.5 m/s (50-100 f/min.)</td>
</tr>
<tr>
<td>aerosols, fumes from pouring operations, intermittent container filling, low speed conveyor transfers, welding, spray drift, plating acid fumes, pickling (released at low velocity into zone of active generation)</td>
<td>0.5-1 m/s (100-200 f/min.)</td>
</tr>
<tr>
<td>direct spray, spray painting in shallow booths, drum filling, conveyor loading, crusher dusts, gas discharge (active generation into zone of rapid air motion)</td>
<td>1-2.5 m/s (200-500 f/min.)</td>
</tr>
<tr>
<td>grinding, abrasive blasting, tumbling, high speed wheel generated dusts (released at high initial velocity into zone of very high rapid air motion).</td>
<td>2.5-10 m/s (500-2000 f/min.)</td>
</tr>
</tbody>
</table>

Within each range the appropriate value depends on:

<table>
<thead>
<tr>
<th>Lower end of the range</th>
<th>Upper end of the range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Room air currents minimal or favourable to capture</td>
<td>1: Disturbing room air currents</td>
</tr>
<tr>
<td>2: Contaminants of low toxicity or of nuisance value only.</td>
<td>2: Contaminants of high toxicity</td>
</tr>
<tr>
<td>3: Intermittent, low production.</td>
<td>3: High production, heavy use</td>
</tr>
<tr>
<td>4: Large hood or large air mass in motion</td>
<td>4: Small hood-local control only</td>
</tr>
</tbody>
</table>

Simple theory shows that air velocity falls rapidly with distance away from the opening of a simple extraction pipe. Velocity generally decreases with the square of distance from the extraction point (in simple cases). Therefore the air speed at the extraction point should be adjusted, accordingly, after reference to distance from the contaminating source. The air velocity at the extraction fan, for example, should be a minimum of 1-2 m/s (200-400 f/min) for extraction of solvents generated in a tank 2 meters distant from the extraction point. Other mechanical considerations, producing performance deficits within the extraction apparatus, make it essential that theoretical air velocities are multiplied by factors of 10 or more when extraction systems are installed or used.

**Personal protection**

- Safety glasses with side shields.
- Chemical goggles.
- Contact lenses may pose a special hazard; soft contact lenses may absorb and concentrate irritants. A written policy document, describing the wearing of lenses or restrictions on use, should be created for each workplace or task. This should include a review of lens absorption and adsorption for the class of chemicals in use and an
account of injury experience. Medical and first-aid personnel should be trained in their removal and suitable equipment should be readily available. In the event of chemical exposure, begin eye irrigation immediately and remove contact lens as soon as practicable. Lens should be removed at the first signs of eye redness or irritation - lens should be removed in a clean environment only after workers have washed hands thoroughly. [CDC NIOSH Current Intelligence Bulletin 59], [AS/NZS 1336 or national equivalent]

<table>
<thead>
<tr>
<th>Skin protection</th>
<th>See Hand protection below</th>
</tr>
</thead>
</table>

**NOTE:**
- The material may produce skin sensitisation in predisposed individuals. Care must be taken, when removing gloves and other protective equipment, to avoid all possible skin contact.
- Contaminated leather items, such as shoes, belts and watch-bands should be removed and destroyed.

The selection of suitable gloves does not only depend on the material, but also on further marks of quality which vary from manufacturer to manufacturer. Where the chemical is a preparation of several substances, the resistance of the glove material can not be calculated in advance and has therefore to be checked prior to the application.

The exact break through time for substances has to be obtained from the manufacturer of the protective gloves and has to be observed when making a final choice.

Suitability and durability of glove type is dependent on usage. Important factors in the selection of gloves include:
- frequency and duration of contact,
- chemical resistance of glove material,
- glove thickness and dexterity

Select gloves tested to a relevant standard (e.g. Europe EN 374, US F739, AS/NZS 2161.1 or national equivalent).
- When prolonged or frequently repeated contact may occur, a glove with a protection class of 5 or higher (breakthrough time greater than 240 minutes according to EN 374, AS/NZS 2161.10.1 or national equivalent) is recommended.
- When only brief contact is expected, a glove with a protection class of 3 or higher (breakthrough time greater than 60 minutes according to EN 374, AS/NZS 2161.10.1 or national equivalent) is recommended.
- Contaminated gloves should be replaced.

Gloves must only be worn on clean hands. After using gloves, hands should be washed and dried thoroughly. Application of a non-perfumed moisturiser is recommended.

Experience indicates that the following polymers are suitable as glove materials for protection against undissolved, dry solids, where abrasive particles are not present:
- polychloroprene.
- nitrile rubber.
- butyl rubber.
- fluorocaoutchouc.
- polyvinyl chloride.

Gloves should be examined for wear and/or degradation constantly.

### Body protection
See Other protection below

### Other protection

- **Overalls.**
- **P.V.C. apron.**
- **Barrier cream.**
- **Skin cleansing cream.**
- **Eye wash unit.**

### Thermal hazards
Not Available

---

**Recommended material(s)**

- **GLOVE SELECTION INDEX**

Glove selection is based on a modified presentation of the: *Forsberg Clothing Performance Index*.
The effect(s) of the following substance(s) are taken into account in the computer-generated selection:
Brunnings Cow Manure Not Available

<table>
<thead>
<tr>
<th>Material</th>
<th>CPI</th>
</tr>
</thead>
</table>

* CPI - Chemwatch Performance Index
A: Best Selection
B: Satisfactory; may degrade after 4 hours continuous immersion
C: Poor to Dangerous Choice for other than short term immersion

**NOTE:** As a series of factors will influence the actual performance of the glove, a final selection must be based on detailed observation.
- Where the glove is to be used on a short term, casual or infrequent basis, factors such as "feel" or convenience (e.g. disposability), may dictate a choice of gloves which might otherwise be unsuitable following current intelligence bulletin 59. [AS/NZS 1336 or National equivalent]

### Respiratory protection

<table>
<thead>
<tr>
<th>Required Minimum Protection Factor</th>
<th>Half-Face Respirator</th>
<th>Full-Face Respirator</th>
<th>Powered Air Respirator</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 10 x ES</td>
<td>P1 Air-line*</td>
<td>-</td>
<td>PAPR-P1</td>
</tr>
<tr>
<td>up to 50 x ES</td>
<td>Air-line**</td>
<td>P2</td>
<td>PAPR-P2</td>
</tr>
<tr>
<td>up to 100 x ES</td>
<td>- P3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100+ x ES</td>
<td>- Air-line**</td>
<td>-</td>
<td>PAPR-P3</td>
</tr>
</tbody>
</table>

* - Negative pressure demand  ** - Continuous flow
A(All classes) = Organic vapours, B AUS or B1 = Acid gasses, B2 = Acid gas or hydrogen cyanide(HCN), B3 = Acid gas or hydrogen cyanide(HCN), E = Sulfur dioxide(SO2), G = Agricultural chemicals, K = Ammonia(NH3), Hg = Mercury, NO = Oxides of nitrogen, MB = Methyl bromide, AX = Low boiling point organic compounds(below...
SECTION 9 PHYSICAL AND CHEMICAL PROPERTIES

Information on basic physical and chemical properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Brown organic solids with an earthy odour; does not mix with water.</td>
</tr>
<tr>
<td>Physical state</td>
<td>Divided Solid</td>
</tr>
<tr>
<td>Odour</td>
<td>Not Available</td>
</tr>
<tr>
<td>Odour threshold</td>
<td>Not Available</td>
</tr>
<tr>
<td>pH (as supplied)</td>
<td>Not Available</td>
</tr>
<tr>
<td>Melting point / freezing point (°C)</td>
<td>Not Available</td>
</tr>
<tr>
<td>Initial boiling point and boiling range (°C)</td>
<td>Not Available</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>Not Available</td>
</tr>
<tr>
<td>Evaporation rate</td>
<td>Not Available</td>
</tr>
<tr>
<td>Flammability</td>
<td>Not Available</td>
</tr>
<tr>
<td>Upper Explosive Limit (%)</td>
<td>Not Available</td>
</tr>
<tr>
<td>Lower Explosive Limit (%)</td>
<td>Not Available</td>
</tr>
<tr>
<td>Vapour pressure (kPa)</td>
<td>Not Available</td>
</tr>
<tr>
<td>Solubility in water (g/L)</td>
<td>Immiscible</td>
</tr>
<tr>
<td>Vapour density (Air = 1)</td>
<td>Not Available</td>
</tr>
<tr>
<td>Molecular weight (g/mol)</td>
<td>Not Available</td>
</tr>
<tr>
<td>Partition coefficient n-octanol / water</td>
<td>Not Available</td>
</tr>
<tr>
<td>Surface Tension (dyn/cm or mN/m)</td>
<td>Not Available</td>
</tr>
<tr>
<td>Taste</td>
<td>Not Available</td>
</tr>
<tr>
<td>Explosive properties</td>
<td>Not Available</td>
</tr>
<tr>
<td>Oxidising properties</td>
<td>Not Available</td>
</tr>
<tr>
<td>pH as a solution(1%)</td>
<td>Not Available</td>
</tr>
<tr>
<td>VOC g/L</td>
<td>Not Available</td>
</tr>
</tbody>
</table>

SECTION 10 STABILITY AND REACTIVITY

Reactivity | See section 7

Chemical stability
- Presence of incompatible materials.
- Product is considered stable.
- Hazardous polymerisation will not occur.

Possibility of hazardous reactions | See section 7

Conditions to avoid | See section 7

Incompatible materials | See section 7

Hazardous decomposition products | See section 5

SECTION 11 TOXICOLOGICAL INFORMATION

Information on toxicological effects

Inhaled

Limited evidence or practical experience suggests that the material may produce irritation of the respiratory system, in a significant number of individuals, following inhalation. In contrast to most organs, the lung is able to respond to a chemical insult by first removing or neutralising the irritant and then repairing the damage. The repair process, which initially evolved to protect mammalian lungs from foreign matter and antigens, may however, produce further lung damage resulting in the impairment of gas exchange, the primary function of the lungs. Respiratory tract irritation often results in an inflammatory response involving the recruitment and activation of many cell types, mainly derived from the vascular system.

Persons with impaired respiratory function, airway diseases and conditions such as emphysema or chronic bronchitis, may incur further disability if excessive concentrations of particulate are inhaled.

If prior damage to the circulatory or nervous systems has occurred or if kidney damage has been sustained, proper screenings should be conducted on individuals who may be exposed to further risk if handling and use of the material result in excessive exposures.

Continued...
Ingestion

Accidental ingestion of the material may be damaging to the health of the individual. Considered an unlikely route of entry in commercial/industrial environments. Ingestion may result in nausea, abdominal irritation, pain and vomiting.

Skin Contact

Limited evidence exists, or practical experience predicts, that the material either produces inflammation of the skin in a substantial number of individuals following direct contact, and/or produces significant inflammation when applied to the healthy intact skin of animals, for up to four hours, such inflammation being present twenty-four hours or more after the end of the exposure period. Skin irritation may also be present after prolonged or repeated exposure; this may result in a form of contact dermatitis (nonallergic). The dermatitis is often characterised by skin redness (erythema) and swelling (oedema) which may progress to blistering (vesiculation), scaling and thickening of the epidermis. At the microscopic level there may be intercellular oedema of the spongy layer of the skin (spongiosis) and intracellular oedema of the epidermis.

Open cuts, abraded or irritated skin should not be exposed to this material. Entry into the blood-stream through, for example, cuts, abrasions, puncture wounds or lesions, may produce systemic injury with harmful effects. Examine the skin prior to the use of the material and ensure that any external damage is suitably protected.

Eye

Limited evidence exists, or practical experience suggests, that the material may cause eye irritation in a substantial number of individuals and/or is expected to produce significant ocular lesions which are present twenty-four hours or more after instillation into the eye(s) of experimental animals. Repeated or prolonged eye contact may cause inflammation characterised by temporary redness (similar to windburn) of the conjunctiva (conjunctivitis); temporary impairment of vision and/or other transient eye damage/ulceration may occur.

Chronic

Practical evidence shows that inhalation of the material is capable of inducing a sensitisation reaction in a substantial number of individuals at a greater frequency than would be expected from the response of a normal population. Pulmonary sensitisation, resulting in hyperactive airway dysfunction and pulmonary allergy may be accompanied by fatigue, malaise and aching. Significant symptoms of exposure may persist for extended periods, even after exposure ceases. Symptoms can be activated by a variety of nonspecific environmental stimuli such as automobile exhaust, perfumes and passive smoking.

Practical experience shows that skin contact with the material is capable either of inducing a sensitisation reaction in a substantial number of individuals, and/or of producing a positive response in experimental animals. Long term exposure to high dust concentrations may cause changes in lung function (i.e. pneumoconiosis) caused by particles less than 0.5 micron penetrating and remaining in the lung. A prime symptom is breathlessness. Lung shadows show on X-ray.

Brunnings Cow Manure

<table>
<thead>
<tr>
<th>Toxicity</th>
<th>Irritation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Available</td>
<td>Not Available</td>
</tr>
</tbody>
</table>

graded sand

<table>
<thead>
<tr>
<th>Toxicity</th>
<th>Irritation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Available</td>
<td>Not Available</td>
</tr>
</tbody>
</table>

Not available. Refer to individual constituents.

GRADED SAND

No significant acute toxicological data identified in literature search.

CMR STATUS

Not Applicable

SECTION 12 ECOLOGICAL INFORMATION

Toxicity

NOT AVAILABLE
### Persistence and degradability

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Persistence: Water/Soil</th>
<th>Persistence: Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Available</td>
<td>Not Available</td>
<td>Not Available</td>
</tr>
</tbody>
</table>

### Bioaccumulative potential

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Bioaccumulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Available</td>
<td>Not Available</td>
</tr>
</tbody>
</table>

### Mobility in soil

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Available</td>
<td>Not Available</td>
</tr>
</tbody>
</table>

### SECTION 13 DISPOSAL CONSIDERATIONS

#### Waste treatment methods

**Product / Packaging disposal**

- Containers may still present a chemical hazard/danger when empty.
- Return to supplier for reuse/recycling if possible.

**Otherwise:**

- If container cannot be cleaned sufficiently well to ensure that residuals do not remain or if the container cannot be used to store the same product, then puncture containers, to prevent re-use, and bury at an authorised landfill.
- Where possible retain label warnings and MSDS and observe all notices pertaining to the product.

Legislation addressing waste disposal requirements may differ by country, state and/or territory. Each user must refer to laws operating in their area. In some areas, certain wastes must be tracked. A Hierarchy of Controls seems to be common - the user should investigate:

- Reduction
- Reuse
- Recycling
- Disposal (if all else fails)

This material may be recycled if unused, or if it has not been contaminated so as to make it unsuitable for its intended use. Shelf life considerations should also be applied in making decisions of this type. Note that properties of a material may change in use, and recycling or reuse may not always be appropriate. In most instances the supplier of the material should be consulted.

- **DO NOT** allow wash water from cleaning or process equipment to enter drains.
- It may be necessary to collect all wash water for treatment before disposal.
- In all cases disposal to sewer may be subject to local laws and regulations and these should be considered first.
- Where in doubt contact the responsible authority.
- Recycle wherever possible.
- Consult manufacturer for recycling options or consult local or regional waste management authority for disposal if no suitable treatment or disposal facility can be identified.
- Dispose of by: burial in a land-fill specifically licenced to accept chemical and/or pharmaceutical wastes or incineration in a licenced apparatus (after admixture with suitable combustible material)
- Decontaminate empty containers. Observe all label safeguards until containers are cleaned and destroyed.

### SECTION 14 TRANSPORT INFORMATION

#### Labels Required

<table>
<thead>
<tr>
<th>Marine Pollutant</th>
<th>HAZCHEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>

**Land transport (ADG): NOT REGULATED FOR TRANSPORT OF DANGEROUS GOODS**

**Air transport (ICAO-IATA / DGR): NOT REGULATED FOR TRANSPORT OF DANGEROUS GOODS**

**Sea transport (IMDG-Code / GGVSSee): NOT REGULATED FOR TRANSPORT OF DANGEROUS GOODS**

### SECTION 15 REGULATORY INFORMATION
Safety, health and environmental regulations / legislation specific for the substance or mixture

graded sand(14808-60-7) is found on the following regulatory lists

*United Nations Consolidated List of Products Whose Consumption and/or Sale Have Been Banned, Withdrawn, Severely Restricted or Not Approved by Governments*, *FisherTransport Information*, *International Agency for Research on Cancer (IARC) - Agents Classified by the IARC Monographs*, *United Arab Emirates Occupational Exposure Limits*, *OECD List of High Production Volume (HPV) Chemicals*, *Sigma-AldrichTransport Information*, *OECD Existing Chemicals Database*

SECTION 16 OTHER INFORMATION

Other information

Classification of the preparation and its individual components has drawn on official and authoritative sources as well as independent review by the Chemwatch Classification committee using available literature references.

A list of reference resources used to assist the committee may be found at:

www.chemwatch.net/references

The (M)SDS is a Hazard Communication tool and should be used to assist in the Risk Assessment. Many factors determine whether the reported Hazards are Risks in the workplace or other settings. Risks may be determined by reference to Exposures Scenarios. Scale of use, frequency of use and current or available engineering controls must be considered.

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1649: Parameterisation of TLUD

Cookstoves to Reduce Emissions

Aleksis Xenophon  a1212995
James Metcalfe  a1211353
Oliver Robson  a1212955

Supplementary Figures

Faculty of Engineering, Computer and Mathematical Sciences
SCHOOL OF MECHANICAL ENGINEERING

THE UNIVERSITY of ADELAIDE

October 23, 2014
Notes

The following document has been prepared at the request of the project supervisors. The document contains figures showing relationships between stove parameter configurations and stove performance measures. It is intended to be used as a reference for future cookstove groups.

Please be aware of the following when interpreting the plots presented:

1. A 14 digit identifier code can be seen at the top of each plot. This code can be used to assist in finding each plot within the 'Figures' folder in the attached CD;

2. dashed red lines shown in a number of figures represent the mean value obtained from natural draft testing;

3. for temperature traces, red solid lines represent the mean temperature within the chimney; blue solid lines represent the mean temperature within the stove. (See Equipment section of the main report for locations at which these measurements were taken);

4. there is a 'Notes’ section at the beginning of each Appendix. Please pay careful attention to these notes, as they may influence how figures are interpreted.
# Contents

Notes i  

A Figures for Primary Airflow Rate Testing 2  
A.1 Emissions Profiles 3  
A.1.1 CO Profiles 3  
A.1.2 H₂ Profiles 4  
A.1.3 NOₓ Profiles 6  
A.1.4 CO₂ Profiles 8  
A.1.5 O₂ Profiles 9  
A.2 Temperature Profiles 11  
A.3 Primary Air Relationships 14  
A.3.1 Emissions 14  
A.3.2 Temperature 24  
A.4 Water Boiling Tests 27  

B Figures for Secondary Airflow Testing 30  
B.1 Emissions Profiles 31  
B.1.1 CO Profiles 31  
B.1.2 H₂ Profiles 32  
B.1.3 NOₓ Profiles 34  
B.1.4 CO₂ Profiles 36
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1.5 O₂ Profiles</td>
<td>37</td>
</tr>
<tr>
<td>B.2 Temperature Profiles</td>
<td>40</td>
</tr>
<tr>
<td>B.3 Secondary Air Relationships</td>
<td>43</td>
</tr>
<tr>
<td>B.3.1 Emissions</td>
<td>43</td>
</tr>
<tr>
<td>B.3.2 Temperature</td>
<td>53</td>
</tr>
<tr>
<td>B.4 Water Boiling Tests</td>
<td>56</td>
</tr>
<tr>
<td>C Figures for Fuel Size Testing</td>
<td>59</td>
</tr>
<tr>
<td>C.1 Emissions Profiles</td>
<td>60</td>
</tr>
<tr>
<td>C.1.1 CO Profiles</td>
<td>60</td>
</tr>
<tr>
<td>C.1.2 H₂ Profiles</td>
<td>61</td>
</tr>
<tr>
<td>C.1.3 NOₓ Profiles</td>
<td>62</td>
</tr>
<tr>
<td>C.1.4 CO₂ Profiles</td>
<td>63</td>
</tr>
<tr>
<td>C.2 Temperature Profiles</td>
<td>64</td>
</tr>
<tr>
<td>C.3 Fuel Size Relationships</td>
<td>66</td>
</tr>
<tr>
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<td>66</td>
</tr>
<tr>
<td>C.3.2 Temperature</td>
<td>76</td>
</tr>
<tr>
<td>C.4 Water Boiling Tests</td>
<td>78</td>
</tr>
<tr>
<td>D Figures for Fuel Grate Location Testing</td>
<td>81</td>
</tr>
<tr>
<td>D.1 Emissions Profiles</td>
<td>82</td>
</tr>
<tr>
<td>D.1.1 CO Profiles</td>
<td>82</td>
</tr>
<tr>
<td>D.1.2 H₂ Profiles</td>
<td>83</td>
</tr>
<tr>
<td>D.1.3 NOₓ Profiles</td>
<td>84</td>
</tr>
<tr>
<td>D.1.4 CO₂ Profiles</td>
<td>86</td>
</tr>
<tr>
<td>D.2 Temperature Profiles</td>
<td>87</td>
</tr>
<tr>
<td>D.3 Fuel Grate Location Relationships</td>
<td>90</td>
</tr>
<tr>
<td>D.3.1 Emissions</td>
<td>90</td>
</tr>
<tr>
<td>D.3.2 Temperature</td>
<td>99</td>
</tr>
</tbody>
</table>
Figures

A.1 CO Emissions Profiles ........................................... 4
A.2 H₂ Emissions Profiles ........................................ 6
A.3 NOₓ Emissions Profiles .......................................... 7
A.4 CO₂ Emissions Profiles ......................................... 9
A.5 O₂ Profiles ......................................................... 11
A.6 Mean temperature of pre and post combusted volatiles .... 13
A.7 Time in Initial Phase ............................................ 14
A.8 Maximum CO Peak in Initial Phase ............................ 14
A.9 Time to Maximum CO Peak in Initial Phase ................. 15
A.10 Maximum H₂ Peak in Initial Phase ......................... 15
A.11 Time to Maximum H₂ Peak in Initial Phase ............... 16
A.12 Time in Steady-State Phase .................................. 16
A.13 Mean CO in Steady-State Phase ............................... 17
A.14 Mean CO₂ in Steady-State Phase ......................... 17
A.15 Mean NOₓ in Steady-State Phase ............................ 18
A.16 Mean O₂ in Steady-State Phase ............................... 18
A.17 Mean H₂ in Steady-State Phase ............................... 19
A.18 Time in Final Phase ........................................... 19
A.19 Maximum CO Peak in Final Phase ............................ 20
A.20 Time to Maximum CO Peak in Final Phase ................. 20
A.21 Maximum H₂ Peak in Final Phase ............................ 21
A.22 Time to Maximum $H_2$ Peak in Final Phase .................................. 21
A.23 Mean CO in Final Phase ................................................................. 22
A.24 Mean $CO_2$ in Final Phase ............................................................... 22
A.25 Mean $NO_X$ in Final Phase .............................................................. 23
A.26 Mean $O_2$ in Final Phase ................................................................. 23
A.27 Mean $H_2$ in Final Phase ................................................................. 24
A.28 Peak initial temperature of pre-combusted volatiles in stove .......... 24
A.29 Time to peak initial temperature of pre-combusted volatiles in stove . 25
A.30 Mean minimum temperature of pre-combusted volatiles in stove in
steady-state .............................................................................................. 25
A.31 Mean time to minimum temperature of pre-combusted volatiles in
stove in steady-state .................................................................................. 26
A.32 Mean maximum chimney temperature of volatiles post combustion . 26
A.33 Water temperature profiles ................................................................. 27
A.34 Maximum water temperature ............................................................. 28
A.35 Time to maximum water temperature ................................................ 28
A.36 Average heating rate ........................................................................... 29
A.37 Heat transferred to pot ......................................................................... 29

B.1 CO Emissions Profiles ................................................................. 32
B.2 $H_2$ Emissions Profiles ................................................................. 34
B.3 $NO_X$ Emissions Profiles ................................................................. 35
B.4 $CO_2$ Emissions Profiles ................................................................. 37
B.5 $O_2$ Profiles ....................................................................................... 39
B.6 Mean temperature of pre and post combusted volatiles ................. 42
B.7 Time in Initial Phase ........................................................................... 43
B.8 Maximum CO Peak in Initial Phase ................................................... 43
B.9 Time to Maximum CO Peak in Initial Phase ...................................... 44
B.10 Maximum $H_2$ Peak in Initial Phase ............................................... 44
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.11</td>
<td>Time to Maximum H\textsubscript{2} Peak in Initial Phase</td>
<td>45</td>
</tr>
<tr>
<td>B.12</td>
<td>Time in Steady-State Phase</td>
<td>45</td>
</tr>
<tr>
<td>B.13</td>
<td>Mean CO in Steady-State Phase</td>
<td>46</td>
</tr>
<tr>
<td>B.14</td>
<td>Mean CO\textsubscript{2} in Steady-State Phase</td>
<td>46</td>
</tr>
<tr>
<td>B.15</td>
<td>Mean NO\textsubscript{X} in Steady-State Phase</td>
<td>47</td>
</tr>
<tr>
<td>B.16</td>
<td>Mean O\textsubscript{2} in Steady-State Phase</td>
<td>47</td>
</tr>
<tr>
<td>B.17</td>
<td>Mean H\textsubscript{2} in Steady-State Phase</td>
<td>48</td>
</tr>
<tr>
<td>B.18</td>
<td>Time in Final Phase</td>
<td>48</td>
</tr>
<tr>
<td>B.19</td>
<td>Maximum CO Peak in Final Phase</td>
<td>49</td>
</tr>
<tr>
<td>B.20</td>
<td>Time to Maximum CO Peak in Final Phase</td>
<td>49</td>
</tr>
<tr>
<td>B.21</td>
<td>Maximum H\textsubscript{2} Peak in Final Phase</td>
<td>50</td>
</tr>
<tr>
<td>B.22</td>
<td>Time to Maximum H\textsubscript{2} Peak in Final Phase</td>
<td>50</td>
</tr>
<tr>
<td>B.23</td>
<td>Mean CO in Final Phase</td>
<td>51</td>
</tr>
<tr>
<td>B.24</td>
<td>Mean CO\textsubscript{2} in Final Phase</td>
<td>51</td>
</tr>
<tr>
<td>B.25</td>
<td>Mean NO\textsubscript{X} in Final Phase</td>
<td>52</td>
</tr>
<tr>
<td>B.26</td>
<td>Mean O\textsubscript{2} in Final Phase</td>
<td>52</td>
</tr>
<tr>
<td>B.27</td>
<td>Mean H\textsubscript{2} in Final Phase</td>
<td>53</td>
</tr>
<tr>
<td>B.28</td>
<td>Peak initial temperature of pre-combusted volatiles in stove</td>
<td>53</td>
</tr>
<tr>
<td>B.29</td>
<td>Time to peak initial temperature of pre-combusted volatiles in stove</td>
<td>54</td>
</tr>
<tr>
<td>B.30</td>
<td>Mean minimum temperature of pre-combusted volatiles in stove in steady-state</td>
<td>54</td>
</tr>
<tr>
<td>B.31</td>
<td>Mean time to minimum temperature of pre-combusted volatiles in stove in steady-state</td>
<td>55</td>
</tr>
<tr>
<td>B.32</td>
<td>Mean maximum chimney temperature of volatiles post combustion</td>
<td>55</td>
</tr>
<tr>
<td>B.33</td>
<td>Water temperature profiles</td>
<td>56</td>
</tr>
<tr>
<td>B.34</td>
<td>Maximum water temperature</td>
<td>57</td>
</tr>
<tr>
<td>B.35</td>
<td>Time to maximum water temperature</td>
<td>57</td>
</tr>
<tr>
<td>B.36</td>
<td>Average heating rate</td>
<td>58</td>
</tr>
<tr>
<td>B.37</td>
<td>Heat transferred to pot</td>
<td>58</td>
</tr>
</tbody>
</table>
C.1 CO Emissions Profiles ........................................ 60
C.2 H$_2$ Emissions Profiles ....................................... 61
C.3 NO$_X$ Emissions Profiles ..................................... 62
C.4 CO$_2$ Emissions Profiles ...................................... 63
C.5 Mean temperature of pre and post combusted volatiles ........ 65
C.6 Time in Initial Phase .......................................... 66
C.7 Maximum CO Peak in Initial Phase ............................ 66
C.8 Time to Maximum CO Peak in Initial Phase ................... 67
C.9 Maximum H$_2$ Peak in Initial Phase ........................... 67
C.10 Time to Maximum H$_2$ Peak in Initial Phase ................. 68
C.11 Time in Steady-State Phase .................................. 68
C.12 Mean CO in Steady-State Phase ............................... 69
C.13 Mean CO$_2$ in Steady-State Phase ............................ 69
C.14 Mean NO$_X$ in Steady-State Phase ............................ 70
C.15 Mean H$_2$ in Steady-State Phase .............................. 70
C.16 Time in Final Phase ......................................... 71
C.17 Maximum CO Peak in Final Phase ............................. 71
C.18 Time to Maximum CO Peak in Final Phase .................... 72
C.19 Maximum H$_2$ Peak in Final Phase ........................... 72
C.20 Time to Maximum H$_2$ Peak in Final Phase .................... 73
C.21 Mean CO in Final Phase ....................................... 73
C.22 Mean CO$_2$ in Final Phase .................................... 74
C.23 Mean NO$_X$ in Final Phase .................................... 74
C.24 Mean H$_2$ in Final Phase ..................................... 75
C.25 Peak initial temperature of pre-combusted volatiles in stove 76
C.26 Time to peak initial temperature of pre-combusted volatiles in stove . 76
C.27 Mean minimum temperature of pre-combusted volatiles in stove in steady-state ........................................ 77
C.28 Mean time to minimum temperature of pre-combusted volatiles in stove in steady-state .......................................................... 77
C.29 Water temperature profiles .................................................. 78
C.30 Maximum water temperature ................................................. 79
C.31 Time to maximum water temperature .................................... 79
C.32 Average heating rate ............................................................ 80
C.33 Heat transferred to pot .......................................................... 80
D.1 CO Emissions Profiles ............................................................ 83
D.2 H\textsubscript{2} Emissions Profiles .............................................. 84
D.3 NO\textsubscript{X} Emissions Profiles ............................................... 85
D.4 CO\textsubscript{2} Emissions Profiles ............................................... 87
D.5 Mean temperature of pre and post combusted volatiles .............. 89
D.6 Time in Initial Phase .............................................................. 90
D.7 Maximum CO Peak in Initial Phase ......................................... 90
D.8 Time to Maximum CO Peak in Initial Phase ............................. 91
D.9 Maximum H\textsubscript{2} Peak in Initial Phase ................................ 91
D.10 Time to Maximum H\textsubscript{2} Peak in Initial Phase ................. 92
D.11 Time in Steady-State Phase ..................................................... 92
D.12 Mean CO in Steady-State Phase ............................................. 93
D.13 Mean CO\textsubscript{2} in Steady-State Phase .................................. 93
D.14 Mean NO\textsubscript{X} in Steady-State Phase .................................. 94
D.15 Mean H\textsubscript{2} in Steady-State Phase ................................... 94
D.16 Time in Steady-State Phase ..................................................... 95
D.17 Maximum CO Peak in Final Phase ......................................... 95
D.18 Time to Maximum CO Peak in Final Phase ............................. 96
D.19 Maximum H\textsubscript{2} Peak in Final Phase ................................ 96
D.20 Time to Maximum H\textsubscript{2} Peak in Final Phase ................. 97
D.21 Mean CO in Final Phase ........................................................ 97
D.22 Mean CO$_2$ in Final Phase ........................................ 98
D.23 Mean NO$_X$ in Final Phase ....................................... 98
D.24 Mean H$_2$ in Final Phase ......................................... 99
D.25 Mean maximum chimney temperature of volatiles post combustion . 99
Appendix A

Figures for Primary Airflow Rate Testing

Notes:

1. Airflow rates in figure captions (e.g. 138 L/min for Figure A.1c) represent the primary airflow rate. Secondary air was entrained naturally through openings in the chimney for all tests involving controlled primary air. Benchmarking profiles refer to the stove configuration where both primary and secondary air was entrained naturally through openings in the stove body and chimney;

2. the O$_2$ sensor within the Testo malfunctioned for tests with primary airflows of 118 L/min. Therefore there is limited O$_2$ data for these plots.
A.1 Emissions Profiles

A.1.1 CO Profiles

(a) Benchmarking - Non-normalized

(b) Benchmarking - Normalized

(c) 138 L/min - Non-normalized

(d) 138 L/min - Normalized

(e) 118 L/min - Non-normalized

(f) 118 L/min - Normalized
A.1. EMISSIONS PROFILES

Figure A.1: CO Emissions Profiles

A.1.2 H$_2$ Profiles

(a) Benchmarking - Non-normalized
(b) Benchmarking - Normalized
A.1. EMISSIONS PROFILES

(c) 138 L/min - Non-normalized

(d) 138 L/min - Normalized

(e) 118 L/min - Non-normalized

(f) 118 L/min - Normalized

(g) 98 L/min - Non-normalized

(h) 98 L/min - Normalized
A.1. EMISSIONS PROFILES

A.1.3 NO\textsubscript{X} Profiles

Figure A.2: H\textsubscript{2} Emissions Profiles

(i) 78 L/min - Non-normalized

(j) 78 L/min - Normalized

(a) Benchmarking - Non-normalized

(b) Benchmarking - Normalized

(c) 138 L/min - Non-normalized

(d) 138 L/min - Normalized
Figure A.3: NO\textsubscript{X} Emissions Profiles
A.1.4 CO₂ Profiles

(a) Benchmarking - Non-normalized

(b) Benchmarking - Normalized

(c) 138 L/min - Non-normalized

(d) 138 L/min - Normalized

(e) 118 L/min - Non-normalized

(f) 118 L/min - Normalized
A.1. EMISSIONS PROFILES

A.1.5 O₂ Profiles

Figure A.4: CO₂ Emissions Profiles
A.1. EMISSIONS PROFILES

(c) 138 L/min - Non-normalized

(d) 138 L/min - Normalized

(e) 118 L/min - Non-normalized

(f) 118 L/min - Normalized

(g) 98 L/min - Non-normalized

(h) 98 L/min - Normalized
A.2. TEMPERATURE PROFILES

Figure A.5: \( O_2 \) Profiles

(i) 78 L/min - Non-normalized
(j) 78 L/min - Normalized

A.2 Temperature Profiles
A.2. TEMPERATURE PROFILES

(b) 138 L/min

(c) 118 L/min
A.2. TEMPERATURE PROFILES

(d) 98 L/min

(e) 78 L/min

Figure A.6: Mean temperature of pre and post combusted volatiles
A.3 Primary Air Relationships

A.3.1 Emissions

Initial Phase

Figure A.7: Time in Initial Phase

Figure A.8: Maximum CO Peak in Initial Phase
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.9: Time to Maximum CO Peak in Initial Phase

Figure A.10: Maximum H₂ Peak in Initial Phase
A.3. PRIMARY AIR RELATIONSHIPS

![Graph: Time to Maximum H₂ Peak in Initial Phase](image)

Figure A.11: Time to Maximum H₂ Peak in Initial Phase

**Steady-State Phase**

![Graph: Time in Steady-State Phase](image)

Figure A.12: Time in Steady-State Phase
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.13: Mean CO in Steady-State Phase

Figure A.14: Mean CO$_2$ in Steady-State Phase
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.15: Mean NO\textsubscript{X} in Steady-State Phase

(a) Non-normalized

(b) Normalized

Figure A.16: Mean O\textsubscript{2} in Steady-State Phase

(a) Non-normalized

(b) Normalized
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.17: Mean H$_2$ in Steady-State Phase

Final Phase

Figure A.18: Time in Final Phase
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.19: Maximum CO Peak in Final Phase

Figure A.20: Time to Maximum CO Peak in Final Phase
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.21: Maximum H$_2$ Peak in Final Phase

Figure A.22: Time to Maximum H$_2$ Peak in Final Phase
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.23: Mean CO in Final Phase

Figure A.24: Mean CO$_2$ in Final Phase
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.25: Mean NO\textsubscript{X} in Final Phase

Figure A.26: Mean O\textsubscript{2} in Final Phase
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.27: Mean $H_2$ in Final Phase

A.3.2 Temperature

Figure A.28: Peak initial temperature of pre-combusted volatiles in stove
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.29: Time to peak initial temperature of pre-combusted volatiles in stove

Figure A.30: Mean minimum temperature of pre-combusted volatiles in stove in steady-state
A.3. PRIMARY AIR RELATIONSHIPS

Figure A.31: Mean time to minimum temperature of pre-combusted volatiles in stove in steady-state

Figure A.32: Mean maximum chimney temperature of volatiles post combustion
A.4 Water Boiling Tests

Figure A.33: Water temperature profiles
A.4. WATER BOILING TESTS

Figure A.34: Maximum water temperature

Figure A.35: Time to maximum water temperature
A.4. WATER BOILING TESTS

Figure A.36: Average heating rate

Figure A.37: Heat transferred to pot
Appendix B

Figures for Secondary Airflow Testing

Notes:

1. Airflow rates in figure captions (e.g. 574 L/min for Figure A.1c) represent the secondary airflow rate. Primary air was controlled at a constant rate of 118 L/min for all tests involving controlled secondary air. Benchmarking profiles refer to the stove configuration where both primary and secondary air was entrained naturally through openings in the stove body and chimney.
B.1 Emissions Profiles

B.1.1 CO Profiles

(a) Benchmarking - Non-normalized  
(b) Benchmarking - Normalized

(c) 574 L/min - Non-normalized  
(d) 574 L/min - Normalized

(e) 492 L/min - Non-normalized  
(f) 492 L/min - Normalized
B.1. EMISSIONS PROFILES

![CO Emissions Profiles](image)

(g) 410 L/min - Non-normalized  
(h) 410 L/min - Normalized  
(i) 328 L/min - Non-normalized  
(j) 328 L/min - Normalized

Figure B.1: CO Emissions Profiles

B.1.2 H₂ Profiles

![H₂ Profiles](image)

(a) Benchmarking - Non-normalized  
(b) Benchmarking - Normalized
B.1. EMISSIONS PROFILES

(c) 574 L/min - Non-normalized

(d) 574 L/min - Normalized

(e) 492 L/min - Non-normalized

(f) 492 L/min - Normalized

(g) 410 L/min - Non-normalized

(h) 410 L/min - Normalized
### B.1.3 NO\textsubscript{x} Profiles

- **(a) Benchmarking - Non-normalized**
  - Time (s) vs. NO\textsubscript{x} (ppm)
  - NO\textsubscript{x} / CO + CO\textsubscript{2}

- **(b) Benchmarking - Normalized**
  - Time (s) vs. NO\textsubscript{x} (ppm)
  - NO\textsubscript{x} / CO + CO\textsubscript{2}

- **(c) 574 L/min - Non-normalized**
  - Time (s) vs. NO\textsubscript{x} (ppm)
  - NO\textsubscript{x} / CO + CO\textsubscript{2}

- **(d) 574 L/min - Normalized**
  - Time (s) vs. NO\textsubscript{x} (ppm)
  - NO\textsubscript{x} / CO + CO\textsubscript{2}

Figure B.2: H\textsubscript{2} Emissions Profiles
B.1. EMISSIONS PROFILES

Figure B.3: NO\textsubscript{X} Emissions Profiles
B.1.4 CO₂ Profiles

(a) Benchmarking - Non-normalized

(b) Benchmarking - Normalized

(c) 574 L/min - Non-normalized

(d) 574 L/min - Normalized

(e) 492 L/min - Non-normalized

(f) 492 L/min - Normalized
B.1. **EMISSIONS PROFILES**

B.1.5 **O₂ Profiles**

Figure B.4: CO₂ Emissions Profiles

(g) 410 L/min - Non-normalized
(h) 410 L/min - Normalized

(i) 328 L/min - Non-normalized
(j) 328 L/min - Normalized

(a) Benchmarking - Non-normalized
(b) Benchmarking - Normalized
B.1. EMISSIONS PROFILES

(c) 574 L/min - Non-normalized

(d) 574 L/min - Normalized

(e) 492 L/min - Non-normalized

(f) 492 L/min - Normalized

(g) 410 L/min - Non-normalized

(h) 410 L/min - Normalized
B.1. EMISSIONS PROFILES

Figure B.5: $O_2$ Profiles

(i) 328 L/min - Non-normalized

(j) 328 L/min - Normalized
B.2 Temperature Profiles

(a) Benchmarking

(b) 574 L/min
B.2. TEMPERATURE PROFILES

(c) 492 L/min

(d) 410 L/min
Figure B.6: Mean temperature of pre and post combusted volatiles

(e) 328 L/min
B.3 Secondary Air Relationships

B.3.1 Emissions

Initial Phase

Figure B.7: Time in Initial Phase

Figure B.8: Maximum CO Peak in Initial Phase
B.3. SECONDARY AIR RELATIONSHIPS

Figure B.9: Time to Maximum CO Peak in Initial Phase

Figure B.10: Maximum H₂ Peak in Initial Phase
B.3. SECONDARY AIR RELATIONSHIPS

Figure B.11: Time to Maximum H₂ Peak in Initial Phase

(a) Non-normalized  (b) Normalized

Figure B.12: Time in Steady-State Phase

(a) Non-normalized
B.3. SECONDARY AIR RELATIONSHIPS

Figure B.13: Mean CO in Steady-State Phase

Figure B.14: Mean CO₂ in Steady-State Phase
B.3. SECONDARY AIR RELATIONSHIPS

Figure B.15: Mean NO\textsubscript{X} in Steady-State Phase

(a) Non-normalized  
(b) Normalized

Figure B.16: Mean O\textsubscript{2} in Steady-State Phase

(a) Non-normalized  
(b) Normalized
B.3. SECONDARY AIR RELATIONSHIPS

Figure B.17: Mean H₂ in Steady-State Phase

Final Phase

Figure B.18: Time in Final Phase
B.3. SECONDARY AIR RELATIONSHIPS

(a) Non-normalized
(b) Normalized

Figure B.19: Maximum CO Peak in Final Phase

(a) Non-normalized
(b) Normalized

Figure B.20: Time to Maximum CO Peak in Final Phase
B.3. SECONDARY AIR RELATIONSHIPS

Figure B.21: Maximum H\textsubscript{2} Peak in Final Phase

Figure B.22: Time to Maximum H\textsubscript{2} Peak in Final Phase
B.3. SECONDARY AIR RELATIONSHIPS

Figure B.23: Mean CO in Final Phase

Figure B.24: Mean CO\textsubscript{2} in Final Phase
B.3. SECONDARY AIR RELATIONSHIPS

Figure B.25: Mean NO\textsubscript{X} in Final Phase

Figure B.26: Mean O\textsubscript{2} in Final Phase
B.3. SECONDARY AIR RELATIONSHIPS

B.3.2 Temperature

Figure B.27: Mean H₂ in Final Phase

Figure B.28: Peak initial temperature of pre-combusted volatiles in stove
Figure B.29: Time to peak initial temperature of pre-combusted volatiles in stove

Figure B.30: Mean minimum temperature of pre-combusted volatiles in stove in steady-state
Figure B.31: Mean time to minimum temperature of pre-combusted volatiles in stove in steady-state

Figure B.32: Mean maximum chimney temperature of volatiles post combustion
B.4 Water Boiling Tests

Figure B.33: Water temperature profiles
Figure B.34: Maximum water temperature

Figure B.35: Time to maximum water temperature
B.4. WATER BOILING TESTS

Figure B.36: Average heating rate

Figure B.37: Heat transferred to pot
Appendix C

Figures for Fuel Size Testing

Notes:

1. Care must be taken when interpreting data for fuel sizes with surface area to volume ratios equal to 0.15. Combustion at the secondary air inlet was not observed for this fuel size. Consequently, the decisions rules used to separate data into different phases could not be applied. The data for this fuel size was separated into phases by visually inspecting the normalized CO traces. The steady-state phase was defined to begin 20 s after ignition and last for 330 s;

2. primary airflow was controlled at 118 L/min for all tests. Secondary air was entrained naturally through openings in the chimney.
C.1 Emissions Profiles

C.1.1 CO Profiles

Figure C.1: CO Emissions Profiles
C.1.2 \( \text{H}_2 \) Profiles

Figure C.2: \( \text{H}_2 \) Emissions Profiles
C.1.3 NO\textsubscript{X} Profiles

![Graphs showing NO\textsubscript{X} emissions profiles for different SA/V ratios.]

(a) 0.15 SA/V - Non-normalized  
(b) 0.15 SA/V - Normalized

(c) 0.19 SA/V - Non-normalized  
(d) 0.19 SA/V - Normalized

(e) 0.22 SA/V - Non-normalized  
(f) 0.22 SA/V - Normalized

Figure C.3: NO\textsubscript{X} Emissions Profiles
C.1.4 CO\textsubscript{2} Profiles

Figure C.4: CO\textsubscript{2} Emissions Profiles
C.2 Temperature Profiles

(c) 0.15 SA/V

(d) 0.19 SA/V
C.2. TEMPERATURE PROFILES

(a) 0.22 SA/V

Figure C.5: Mean temperature of pre and post combusted volatiles
C.3 Fuel Size Relationships

C.3.1 Emissions

Initial Phase

Figure C.6: Time in Initial Phase

Figure C.7: Maximum CO Peak in Initial Phase
C.3. FUEL SIZE RELATIONSHIPS

Figure C.8: Time to Maximum CO Peak in Initial Phase

Figure C.9: Maximum H\textsubscript{2} Peak in Initial Phase
C.3. FUEL SIZE RELATIONSHIPS

Figure C.10: Time to Maximum H₂ Peak in Initial Phase

Steady-State Phase

Figure C.11: Time in Steady-State Phase
C.3. FUEL SIZE RELATIONSHIPS

Figure C.12: Mean CO in Steady-State Phase

Figure C.13: Mean CO$_2$ in Steady-State Phase
C.3. FUEL SIZE RELATIONSHIPS

Figure C.14: Mean NO\textsubscript{X} in Steady-State Phase

Figure C.15: Mean H\textsubscript{2} in Steady-State Phase
C.3. FUEL SIZE RELATIONSHIPS

Final Phase

Figure C.16: Time in Final Phase

Figure C.17: Maximum CO Peak in Final Phase
C.3. FUEL SIZE RELATIONSHIPS

Figure C.18: Time to Maximum CO Peak in Final Phase

Figure C.19: Maximum H$_2$ Peak in Final Phase
C.3. FUEL SIZE RELATIONSHIPS

Figure C.20: Time to Maximum H\textsubscript{2} Peak in Final Phase

Figure C.21: Mean CO in Final Phase
C.3. FUEL SIZE RELATIONSHIPS

Figure C.22: Mean CO\textsubscript{2} in Final Phase

Figure C.23: Mean NO\textsubscript{X} in Final Phase
Figure C.24: Mean $H_2$ in Final Phase

(a) Non-normalized

(b) Normalized
C.3. FUEL SIZE RELATIONSHIPS

C.3.2 Temperature

Figure C.25: Peak initial temperature of pre-combusted volatiles in stove

Figure C.26: Time to peak initial temperature of pre-combusted volatiles in stove
Figure C.27: Mean minimum temperature of pre-combusted volatiles in stove in steady-state

Figure C.28: Mean time to minimum temperature of pre-combusted volatiles in stove in steady-state
C.4 Water Boiling Tests

Figure C.29: Water temperature profiles
C.4. WATER BOILING TESTS

Figure C.30: Maximum water temperature

Figure C.31: Time to maximum water temperature
C.4. WATER BOILING TESTS

Figure C.32: Average heating rate

Figure C.33: Heat transferred to pot
Appendix D

Figures for Fuel Grate Location Testing

Notes:

1. The length values shown in figure captions (e.g. 370 mm for Figure D.1a) represent the separation distance between the top of the fuel stack and the centre of the secondary air inlet. This distance was measured prior to lighting the stove for each test;

2. the primary airflow rate was controlled at 118 L/mim, while secondary air was entrained naturally through openings in the chimney.
D.1 Emissions Profiles

D.1.1 CO Profiles

(a) 370 mm - Non-normalized

(b) 370 mm - Normalized

(c) 270 mm - Non-normalized

(d) 270 mm - Normalized

(e) 170 mm - Non-normalized

(f) 170 mm - Normalized
D.1. EMISSIONS PROFILES

Figure D.1: CO Emissions Profiles

D.1.2 H₂ Profiles

Figure D.1: H₂ Emissions Profiles
D.1. EMISSIONS PROFILES

D.1.3 \textbf{NO}_x\textbf{ Profiles}

Figure D.2: H\textsubscript{2} Emissions Profiles

(a) 370 mm - Non-normalized
(b) 370 mm - Normalized

(e) 170 mm - Non-normalized
(f) 170 mm - Normalized

(g) 80 mm - Non-normalized
(h) 80 mm - Normalized
D.1. EMISSIONS PROFILES

Figure D.3: NO\textsubscript{X} Emissions Profiles
D.1.4 CO₂ Profiles

(a) 370 mm - Non-normalized
(b) 370 mm - Normalized
(c) 270 mm - Non-normalized
(d) 270 mm - Normalized
(e) 170 mm - Non-normalized
(f) 170 mm - Normalized
D.2 TEMPERATURE PROFILES

Figure D.4: CO₂ Emissions Profiles

D.2 Temperature Profiles

(b) 370 mm
D.2. TEMPERATURE PROFILES

(a) 270 mm

(b) 170 mm
Figure D.5: Mean temperature of pre and post combusted volatiles

(c) 80 mm
D.3 Fuel Grate Location Relationships

D.3.1 Emissions

Initial Phase

Figure D.6: Time in Initial Phase

Figure D.7: Maximum CO Peak in Initial Phase
D.3. FUEL GRATE LOCATION RELATIONSHIPS

(a) Non-normalized

(b) Normalized

Figure D.8: Time to Maximum CO Peak in Initial Phase

(a) Non-normalized

(b) Normalized

Figure D.9: Maximum H$_2$ Peak in Initial Phase
D.3. FUEL GRATE LOCATION RELATIONSHIPS

Figure D.10: Time to Maximum H\textsubscript{2} Peak in Initial Phase

Steady-State Phase

Figure D.11: Time in Steady-State Phase
D.3. FUEL GRATE LOCATION RELATIONSHIPS

![Graph of CO (ppm) vs. Top of Stack to Secondary Air Inlet (mm)](image1)

(a) Non-normalized
(b) Normalized

Figure D.12: Mean CO in Steady-State Phase

![Graph of CO₂ (ppm) vs. Top of Stack to Secondary Air Inlet (mm)](image2)

(a) Non-normalized
(b) Normalized

Figure D.13: Mean CO₂ in Steady-State Phase
D.3. FUEL GRATE LOCATION RELATIONSHIPS

Figure D.14: Mean NO\textsubscript{x} in Steady-State Phase

Figure D.15: Mean H\textsubscript{2} in Steady-State Phase
Final Phase

Figure D.16: Time in Steady-State Phase

Figure D.17: Maximum CO Peak in Final Phase
D.3. FUEL GRATE LOCATION RELATIONSHIPS

Figure D.18: Time to Maximum CO Peak in Final Phase

Figure D.19: Maximum H₂ Peak in Final Phase
D.3. FUEL GRATE LOCATION RELATIONSHIPS

Figure D.20: Time to Maximum H₂ Peak in Final Phase

Figure D.21: Mean CO in Final Phase
D.3. FUEL GRATE LOCATION RELATIONSHIPS

Figure D.22: Mean CO$_2$ in Final Phase

Figure D.23: Mean NO$_X$ in Final Phase
D.3. FUEL GRATE LOCATION RELATIONSHIPS

D.3.2 Temperature

Figure D.25: Mean maximum chimney temperature of volatiles post combustion