

# Assessment of Smouldering as an Efficient and Low-Cost Alternative for Management of Agricultural Solid Wastes

---

**PROJECT CODE:** 2017/1037

---

**PREPARED BY:** Luis Yerman, Ilje Pikaar, Paul Jensen

---

**DATE SUBMITTED:** xxx

---

**DATE PUBLISHED:** XXX

---

**PUBLISHED BY:** XXX

---

The Australian Meat Processor Corporation acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

Disclaimer:

The information contained within this publication has been prepared by a third party commissioned by Australian Meat Processor Corporation Ltd (AMPC). It does not necessarily reflect the opinion or position of AMPC. Care is taken to ensure the accuracy of the information contained in this publication. However, AMPC cannot accept responsibility for the accuracy or completeness of the information or opinions contained in this publication, nor does it endorse or adopt the information contained in this report.

No part of this work may be reproduced, copied, published, communicated or adapted in any form or by any means (electronic or otherwise) without the express written permission of Australian Meat Processor Corporation Ltd. All rights are expressly reserved. Requests for further authorisation

## TABLE OF CONTENTS

### TABLE OF CONTENTS 2

|  |    |
|--|----|
| 1 EXECUTIVE SUMMARY  | 4  |
| 2 PROJECT BACKGROUND   | 6  |
| 2.1 Summary of Waste Production  | 6  |
| 2.2 Solids Collection and Screening  | 8  |
| 2.3 Current and Emerging Resource Recovery Technologies                    | 9  |
| 2.3.1 Resource Recovery Technologies – Energy Recovery                     | 10 |
| 2.3.2 Thermal Processing – Nutrient Recovery                               | 13 |
| 2.3.3 Resource Recovery – Alternative Value-add technologies               | 15 |
| 3 PROJECT OBJECTIVES   | 17 |
| 4 LOW TEMPERATURE SMOULDERING REVIEW                                       | 17 |
| 4.1 Summary  | 17 |
| 4.2 Operating Principle  | 19 |
| 4.3 Incineration and the Formation of NO <sub>x</sub>                      | 22 |
| 4.4 Smouldering Emissions  | 22 |
| 4.5 Application to the Red Meat Industry                                   | 26 |
| 5 METHODOLOGY  | 29 |
| 5.1 Stage 1: Desktop analysis and basic feasibility                        | 29 |
| 5.2 Stage 2: Technical feasibility through batch testing                   | 29 |
| 5.3 Stage 3: Development of a continuous process and dynamic field testing | 30 |
| 6 SMOULDERING LABORATORY RESULTS   | 30 |
| 6.1 Paunch Sample Collection   | 30 |
| 6.2 Experimental set-up  | 31 |
| 6.3 Results  | 32 |
| 6.3.1 Paunch characterization  | 32 |
| 6.3.2 Smouldering experiments  | 35 |
| 6.4 Summary of Outcomes  | 38 |

|       |                                    |    |
|-------|------------------------------------|----|
| 7     | DEVELOPMENT OF SMOULDERING PILOT   | 39 |
| 7.1   | Stage 1 Pilot Plant                | 39 |
| 7.1.1 | Stage 1 Pilot Plant Design         | 39 |
| 7.1.2 | Stage 1 Pilot Plant Testing        | 44 |
| 7.1.3 | Major Challenges – Odor Management | 47 |
| 7.2   | Stage 2 Pilot Plant                | 47 |
| 7.2.1 | Stage 2 Pilot Plant Design         | 47 |
| 7.2.2 | Stage 2 Pilot Plant Testing        | 53 |
| 7.2.3 | Major Challenges                   | 56 |
| 7.3   | Further Development Required       | 56 |
| 8     | PRELIMINARY COST BENEFIT ANALYSIS  | 59 |
| 9     | CONCLUSIONS/ RECOMMENDATIONS       | 61 |
| 10    | BIBLIOGRAPHY                       | 62 |
| 11    | APPENDIX                           | 71 |

## 1 EXECUTIVE SUMMARY

Australian slaughterhouses have the potential to generate large volumes of solid waste, originating in a number of processing areas with key sources including paunch, manure, screenings (not rendered), DAF sludge, aerobic wastewater sludge, contaminated cardboard and condemned/dead animals. Cattle paunch in particular is a major waste produced at cattle slaughterhouses and is comprised of partially digested cattle feed, mainly containing grass and grain. The volume and composition of paunch waste varies according to individual animals and site handling practices but is reported at approximately 60 kg of wet paunch waste per animal (5-7 kg solids), corresponding to approximately 10% of the total weight of the live animal. Common existing methods such as composting, direct land application and/or anaerobic digestion are either expensive, facing increasing environmental regulation or not applied to maximize the potential value in RMP waste, therefore effective and low cost management of RMP solid waste remains an industry wide challenge.

Smouldering combustion has emerged as an alternative treatment option for organic solid wastes with high moisture contents (80-85% wt), with some success in similar applications from other industries. The key advantage of the smouldering technology is that stable process performance can be achieved at very high moisture content without the need for external fuel and/or energy input. This key feature allows for treatment of problematic (high moisture, low caloric value) waste streams where alternate treatment methods (e.g. anaerobic digestion) are less attractive. As a stand-alone technology, smouldering is able to deliver value through complete dewatering combined with significant reduction in waste solids mass and volume. As a guide, smouldering has the capacity to reduce 1 ton of dewatered meat processing solid organic waste (moisture content 75-80% wt and organic solids at 90% of dry matter) to approximately 20-30 kg of ash, without the need for external fuel or heat input.

Importantly, smouldering can be applied to these wastes directly, or after application of energy recovery technologies such as Anaerobic Digestion. The use of anaerobic digestion as a smouldering pre-treatment will not impact the final solids for disposal, however AD may improve paunch dewatering and facilitate energy recovery in the order of 8GJ/dry ton paunch.

Proof-of-concept testing has been conducted at laboratory scale, with the following outcomes:

- Self-sustaining smouldering of paunch can be achieved without the addition of a porous sand medium, this may reduce the complexity of plant design and operation (i.e. no required to mix paunch and sand before smouldering and no requirement to separate ash and sand after smouldering).
- Results showed that the limits for moisture content and air flowrate are 75% and 1 cm/s, respectively. This result demonstrates that smouldering could be applied to many RMP using existing paunch dewatering technologies, no addition pre-drying is required. Small scale laboratory experiments are less efficient than large scale reactors, therefore these results are expected to be conservative and further improvements are expected.
- The maximum smouldering temperature increases when the moisture content is decreased, reaching over 1000 °C at 65% moisture. However, the destruction rate decreases. Higher temperatures may increase the risk of NO<sub>x</sub> in the flue gas.
- The maximum smouldering temperature increases in a near linear relationship when air flowrate increases. However, the impact on the temperature can be neglected.

Scale-up and batch field experiments conducted during the project were less successful. Reactor designs require a degree of modification to ensure moisture is removed from the process efficiently and does not lead to combustion quenching. However, most critically, odor was identified as a major barrier that must be addressed in order to continue onsite development of smouldering technology at Australian RMP. This was an initial proof-of-concept project and development and testing of odor management technology was beyond the scope of the current work. Literature was used to develop a conceptual flue-gas treatment system containing i) after burner, ii) wet scrubber, iii) bag filter and iv) activated carbon, however this treatment train was not constructed for testing and odor management remains a critical area for continued development.

Based on the results in this report, smouldering technology is not recommended for RMP until odor management issues can be addressed in a robust and cost effective manner.

## 2 PROJECT BACKGROUND

### 2.1 Summary of Waste Production

Australian slaughterhouses have the potential to generate large volumes of solid waste, originating in a number of processing areas with key sources including paunch, manure, screenings (not rendered), DAF sludge, aerobic wastewater sludge, contaminated cardboard and condemned/dead animals. Cattle paunch in particular is a major waste produced at cattle slaughterhouses and is comprised of partially digested cattle feed, mainly containing grass and grain. The volume and composition of paunch waste varies according to individual animals and site handling practices but is reported at approximately 60 kg of wet paunch waste per animal (5-7 kg solids), corresponding to approximately 10% of the total weight of the live animal.

Fatty tissues (FOGs) represent an estimated 4% of cattle (24kg per animal) and 3% of sheep (1.8kg per animal) live weight. While many RMPs capture FOGs as byproduct (i.e. edible tallow), there remains a significant portion of FOG in RMP wastewater. Previous MLA/AMPC projects report wastewater production in the range of 5-10kL per tHSCW containing an average of 23kg of FOG (A.ENV.0131, A.ENV.151, A.ENV.133/149). A portion of this FOG may be captured using screens, save-alls or dissolved air flotation vessels. Depending on the quality of the screenings, the material may be recycled to rendering or disposed as waste. For large

Waste activated sludge, generated from biological wastewater treatment processes is a solid waste stream of emerging importance for the red meat processing industry. Over the past 10 years, increased environmental regulations has resulted in increased uptake of nitrogen removal processes and subsequently increased production of waste activated sludge at Australian red meat processing plants. Waste activated sludge production is heavily dependent on the configuration of the nitrogen removal technology, but is typically in the range of 1 – 2 kg dry weight per animal processed, combined with conventional dewaterability metrics this corresponded to 10 – 30 kg of solid waste requiring disposal from the site.

Based on the October 2012 survey (MLA/AMPC. 2013) the vast majority of solid wastes are re-used in agriculture either via direct land application (21%) or through composting and land application (66%). While in some cases there is no cost to the plants for paunch disposal the average cost of a cattle only facility was \$13.50/m<sup>3</sup> (highest cost was \$30/m<sup>3</sup>). With the average dewatered paunch production of 0.03 m<sup>3</sup>/head, paunch disposal costs are estimated in the range of \$0.41 to \$0.90 per head. Costs were higher for sheep only facilities at an average of \$34.20/m<sup>3</sup> (highest cost was \$90/m<sup>3</sup>); and the average for a mixed species facility was \$45.50/m<sup>3</sup> (highest cost was \$170/m<sup>3</sup>).

The management of solid wastes from abattoirs and rendering plants is facing increasing environmental legislation.

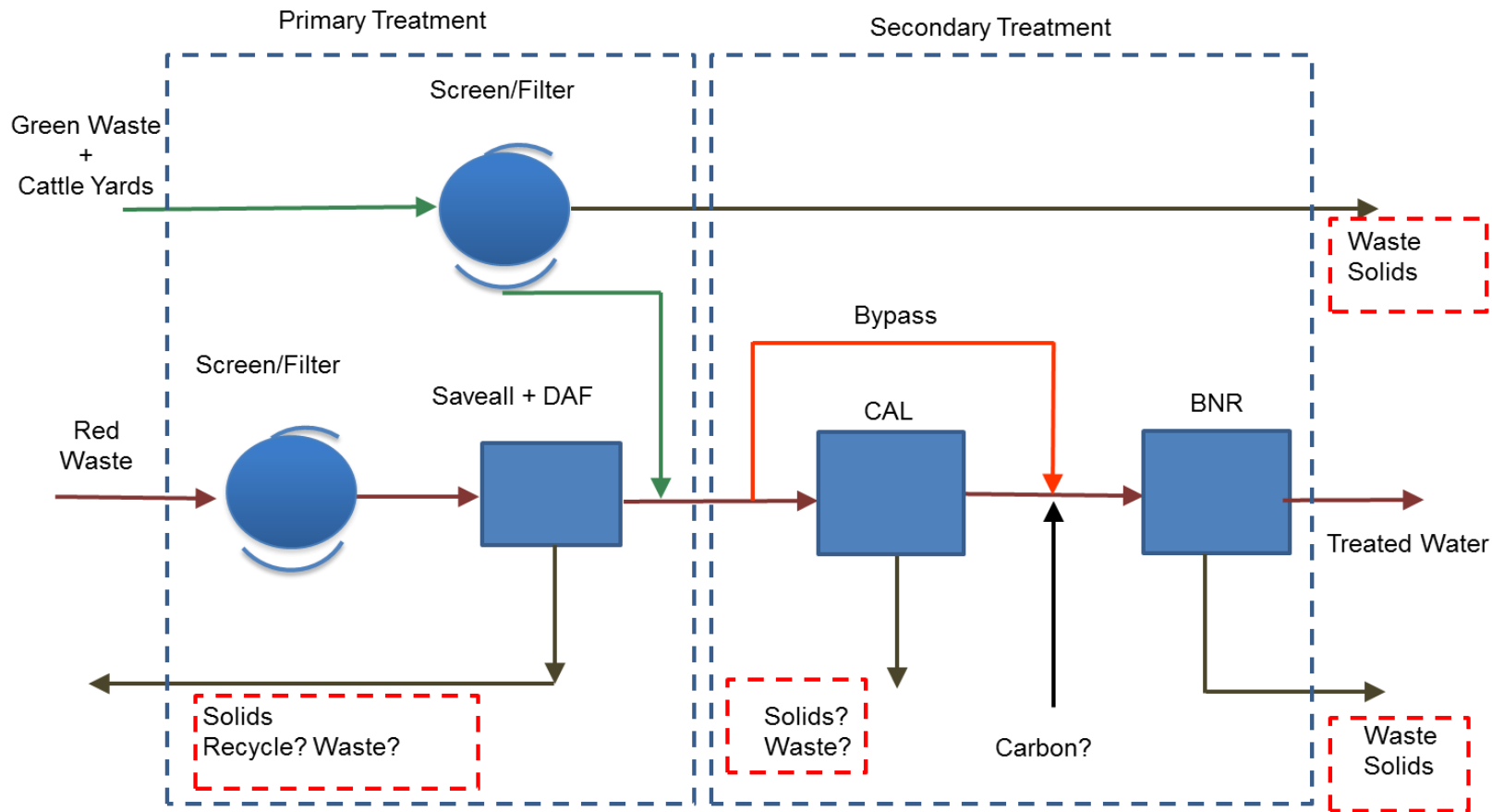


Figure 1: Example of waste handling process at Australian red meat processing facilities and major sources of organic solid waste (not including dead animals or packing wastes).

## 2.2 Solids Collection and Screening

In October 2012, an AMPC survey (MLA/AMPC. 2013) of 31 cattle only, sheep only and cattle/sheep slaughterhouses reported that paunch waste was screened at approximately 90% of respondents and further dewatered at over 50% of respondents. Screw presses were the most common dewatering units. The solids content of dewatered paunch cake was highly variable ranging from 15% up to 75% with an average value of 38%. Variations in paunch properties, possibly related to animal type or diet; variations in dewatering operations and errors in analytical methods are possible factors the results.

In plants using wet dump paunch handling processes, the solids content of paunch waste typically varies in the range of 5,000 mg/L TSS to 30,000 mg/L TSS prior to solids capture. The reported effectiveness of solids and nutrient capture during paunch dewatering processes varied between studies (MLA/AMPC 2012, 2013, MLA/AMPC. 2013). Generally 60-80% of paunch solids will be captured in the dewatered cake, however this may be increased to over 95% by adding chemical agents.

Recovery of phosphorus and potassium during dewatering is generally poor with 75-90% of P and K remaining in the wastewater filtrate. Recovery of nitrogen was more variable with 50-90% of N remaining in the wastewater filtrate, however nitrogen capture can be significantly improved by adding chemical agents during dewatering. Therefore, while paunch dewatering units as an effective strategy for reducing solids they are not an effective strategy for reducing nutrient loads.

A brief summary of dewatering units and operational considerations are shown in Table 1.

**Table 1: Summary of common equipment used for solids recovery from paunch**

|                    | Static Screen  | Rotary Screen                        | Screw Press  | Degritting Hydrocyclone                   |
|--------------------|--|--------------------------------------|--|---|
| Capital Cost       | Low (\$15-20k)   | Low (\$15-20k)                       | Moderate (\$50-80k)  | Moderate (\$50-80k)                       |
| Operating Cost     | Low  | Low                                  | Moderate   | Low                                       |
| Life expectancy    | Long   | Long                                 | Component replacement(s) after 10 years. Screens are subject to wear and may require replacement after 2-3 years | Moderate life                             |
| Application Area   | Gross and Paunch Solids                                | All Solids                           | Paunch and Manure Solids   | Stockyard Grit                            |
| Solids Cake        | Wet  | Wet                                  | Dry (up to 50% solids)   | Wet                                       |
| Operating Weakness | Susceptible to hydraulic overloading and weir blockage | Susceptible to hydraulic overloading | Susceptible to damage from boluses or a lack of fibrous solids; damage from metallic objects in waste streams    | Susceptible to blockage from paunch balls |



### 2.3 Current and Emerging Resource Recovery Technologies

This Section 5.3 describes common existing and developing methods that may be suitable for managing RMP solid waste. Common existing methods such as composting, direct land application and/or anaerobic digestion are either expensive, facing increasing environmental regulation or not applied to maximize the potential value in RMP waste, therefore effective and low cost management of RMP solid waste remains an industry wide challenge. Figure 2 is an example of current and emerging technologies to recover value from organic wastes, grouped into technologies for energy, nutrients and/or value-add products. The following section provides preliminary details on the technologies, including key products, technology readiness level (TRL – detailed in Appendix) and suitability for Red Meat Processing waste applications. More detailed information on the technologies will be presented in the final report.

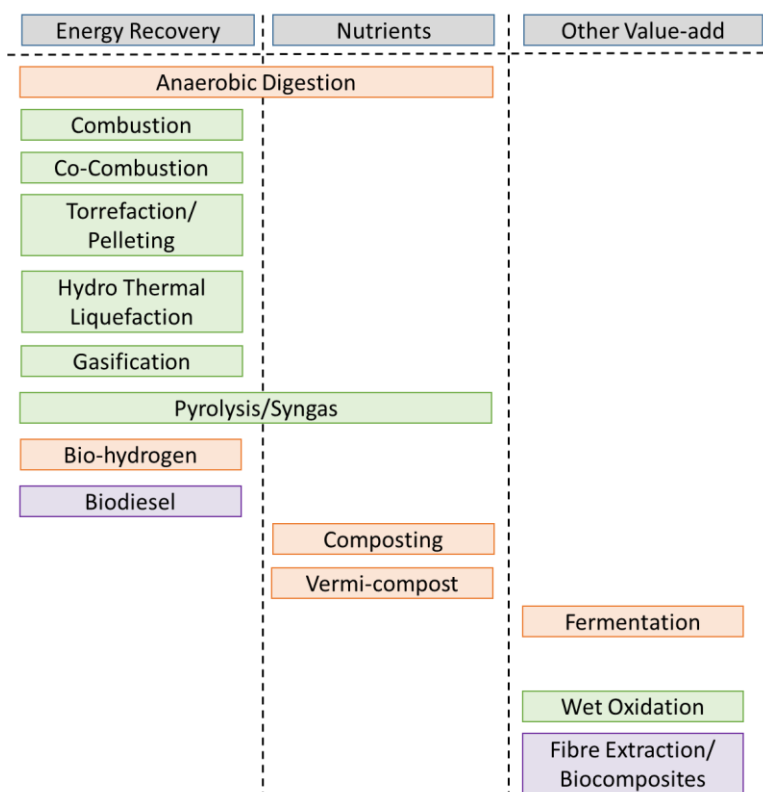


Figure 2: Summary of resource recovery technologies, grouped into energy, nutrient and/or alternative value-add applications (Orange – biological; Green – Thermal processing; Purple – other physical processes).

From a preliminary review of technologies, it is evident that treatment of solid waste is an area of active technology development with a clear shift in focus from waste disposal to resource recovery technologies. Although, there are many technologies under development, anaerobic digestion followed by land application is the most commonly considered for value recovery across the broadest range of industries in Australia and internationally, however this technology requires further optimization to improve the economics. Thermal processes, such as co-combustion are more readily applied internationally due to very strict regulations around landfilling and land application. Thermal processes are rarely applied in Australia, but new technologies with lower costs are emerging.

### 2.3.1 Resource Recovery Technologies – Energy Recovery

Table 2 provides a summary of energy recovery technologies, including key products, technology readiness level (TRL – detailed in Appendix) and suitability for red meat processing applications.

**Table 2: Summary of Resource Recovery Technologies used for Energy Recovery**

| Name   | Description   | Products                               | TRL      | Suitability RMP |
|--|---|--|----------|-----------------|
| <p><b>Anaerobic digestion</b></p> <p><b>(Appels et al. 2008)</b></p> <p><b>For: All RMP organic wastes</b></p> | <p>Biological process that occurs in the absence of oxygen and converts organic material into biogas (methane-rich gas) and a stabilized digestate in the absence of oxygen. Generally less than 50% of solid waste will decompose and be converted to biogas</p> <p>Technically applicable to all RMP wastes, however the feasibility of this technology depends on the biological degradability of the material – determined using BMP testing.</p> <p>Methane yields and digestate stability are subject to sludge characteristics and process operating conditions.</p> <p>May be implemented as low cost lagoons, however addition of RMP solid waste to lagoons is not recommended as lagoons will accumulated solids rapidly and require expensive dredging, desludging and disposal operations.</p> <p>May be implemented as invessel AD, which is widely implemented at medium/large STPs. Conversion of solids is still approximately 50%, however the process is designed for constant</p> | <p>Biogas (E)</p> <p>Biosolids (N)</p> | <p>9</p> | <p>High</p>     |

| Name  | Description  | Products   | TRL | Suitability RMP |
|---|--|--|-----|-----------------|
|   | <p>removal and separate of the digestate. In vessel digestion is generally more expensive than lagoon technologies.</p> <p>AD residues may be applied to land as an organic fertiliser or further treated using thermal processing technologies.</p>   |  |     |                 |
| <p><b>(Co-) Combustion</b></p> <p><b>(Donatello and Cheeseman 2013, Fytili and Zabaniotou 2008, Husillos Rodríguez et al. 2013)</b></p> <p><b>For: All RMP organic wastes</b></p> | <p>Thermal process where the organic content of waste is oxidised into CO<sub>2</sub> and H<sub>2</sub>O and heat energy is released. Requires excess oxygen concentration (related to COD). Can be applied to raw dewatered sludge or residues after AD.</p> <p>Moisture does not contribute chemical energy, but vaporises and consumes the heat released during combustion. Therefore, wastes generally needs to be dried for efficient combustion.</p> <p>Important consideration include: Adequacy of the combustion chamber to manage the volatility of the dried sludge. Adequacy of the gas treatment line to handle the higher NO<sub>x</sub> and particles emissions.</p> <p>Mineral content of waste generally remains as ash. Ashes are potentially used on land as fertilizer or incorporated in cements, brick, etc.</p> <p>Combustion achieves the largest reduction of the SS volume.</p> <p>Most commonly applied outside Australia and at centralised facilities with low land availability.</p> | <p>Thermal and electrical energy</p> <p>Ashes (N, V<sub>add</sub>)</p> | 8   | Medium          |
| <p><b>Torrefaction/ Pelletting (Li et al. 2015)</b></p> <p><b>For: All RMP organic wastes</b></p>   | <p>Thermal process (200 – 400 °C) used as a pre-treatment or conditioning step prior to further thermal processing, such as combustion or pyrolysis. Torrefaction dries waste and removes volatile compounds with lower calorific value. The resulting pellets are generally dry and energy dense.</p> <p>Pellets are easier to transport and store. The waste pellets after torrefaction have better properties for energy generation than just</p>   | <p>Pelleted Biomass/ fuel</p> <p>(V<sub>add</sub>)</p>                 | 6   | Medium/<br>Low  |

| Name  | Description  | Products  | TRL | Suitability RMP |
|---|--|---|-----|-----------------|
|   | <p>dewatered and dried waste.</p> <p>Technology already used for other types of biomass. It can be co-pelletised with other biomass/waste. Existing market demand for pellets as multi-fuel boiler feed.</p>   |   |     |                 |
| <p><b>HydroThermal Liquefaction</b></p> <p><b>For: All RMP organic wastes</b></p>                               | <p>waste decomposition at high temperature (300-400 °C) and pressure (~200 atm) into biocrude oil.</p> <p>Dewatering or pre-drying of waste is not required.</p> <p>Feedstock flexible.</p> <p>Bio-oil properties are comparable to fossil crude oil.</p> <p>Promising technology under development. But limited commercial application and this increases risk.</p> <p>Requires energy input. Biocrude yields and energy balances need to be assessed.</p>  | Bio-oil (E)   | 5   | Medium/<br>High |
| <p><b>Gasification</b></p> <p><b>(Fytili and Zabaniotou 2008)</b></p> <p><b>For: All RMP organic wastes</b></p> | <p>Thermal process that decomposes organic matter at elevated temperature (1000 °C) at a limited oxygen concentration.</p> <p>Gasification generally produces are larger volume of ash than oxygen rich combustion, and may produce a value-add char.</p> <p>A portion of syngas is often used to supply energy to the process. The energy balance is highly sensitive to moisture content and the waste needs to be dried before thermal processing.</p> <p>Technology under development. Few applications worldwide.</p> | <p>Syngas (CO &amp; H<sub>2</sub>)</p> <p>Ashes</p> | 6   | Medium          |
| <p><b>Pyrolysis/Syngas</b></p> <p><b>(Fonts et al. 2012)</b></p>  | <p>Thermal process that decomposes organic matter at elevated temperature (300-800 °C) in the absence of oxygen.</p> <p>Product proportions are affected by process</p>  | <p>Syngas</p> <p>Tar/Oil</p>                        | 6   | Medium/<br>High |

| Name  | Description   | Products  | TRL | Suitability RMP |
|---|---|---|-----|-----------------|
| <b>For: All RMP organic wastes</b>  | <p>conditions and feedstock composition.</p> <p>Biochar makes the heavy metals in the waste more resistant to lixiviation.</p> <p>The energy balance is highly sensitive to moisture content and the waste needs to be dried before thermal processing.</p>   | <p>(V<sub>add</sub> / E)</p> <p>Char (solid)</p> <p>(V<sub>add</sub> / E)</p> |     |                 |
| <b>Bio-hydrogen</b><br><br><b>For: All RMP organic wastes</b>             | <p>Biological process that degrades waste into a hydrogen-rich biogas. Needs to be followed by anaerobic digestion.</p> <p>Energy balances and cost benefit are not clear. Limited evidence that the additional capital and operation costs are offset by the energy production.</p> <p>Bio-hydrogen production can be coupled with fermentation.</p>   | <p>Biogas (E)</p> <p>Carboxylic acids (V<sub>add</sub>)</p>                   | 6   | Medium/<br>Low  |
| <b>Biodiesel</b><br><br><b>For: DAF sludge and other high fat streams</b> | <p>Production of a biodiesel after extraction of fat, oil and grease from waste (note: this is a different form of oil to the bio-crude generated from some thermal processes).</p> <p>The low lipid yields in the waste combined with the high cost of the extraction process makes this technology unsuitable to most sludge streams. The technology is suited to wastes with high lipid content.</p> | Biodiesel (E)   | 8   | Low             |

Notes: E: energy recovery; N: nutrient recovery; V<sub>add</sub>: value-add product; GHG: greenhouse gases.

### 2.3.2 Thermal Processing – Nutrient Recovery

Table 3 provides further details on nutrient recovery technologies, including key products, technology readiness level (TRL – detailed in Appendix) and suitability for sewage sludge applications. Technologies that enable energy recovery and nutrient recovery, such as anaerobic digestion and pyrolysis are included in Table 2 and not repeated in Table 3.

**Table 3: Summary of Resource Recovery Technologies used for Nutrient Recovery**

| Name                                | Description   | Products    | TRL | RMP suitability |
|-------------------------------------|---|-------------|-----|-----------------|
| <b>Composting (Wei et al. 2001)</b> | <p>Microbial process that converts waste into compost (stable organic matter).</p> <p>That are multiple technologies configurations, many are low-tech low-cost technologies. All forms of composting produce a stable final material that can be sold or applied as a soil conditioner. However, the value of the compost may be lower than the cost of production. Pre-drying waste or blending with dry materials may be required.</p> <p>GHG emissions and odours may be high.</p> <p>Energy content is not recovered, however nutrients may be recycled as compost product.</p> <p>Commercially applied in RMP (particularly Australia), but facing increasing regulation and diminishing practice in favour of anaerobic digestion and co-combustion.</p> | Compost (N) | 9   | Medium/High     |
| <b>Vermi-compost</b>                | <p>Vermicomposting is a variation on the composting process using various species of worms. The resulting vermicast is claimed to be of high value. However, the process requires significant investment and ongoing management. Specific performance will depend on the waste characteristics and the species of worms or larvae grown.</p> <p>Energy content is not recovered, however vermi-compost is generally rich in water soluble nutrients and is a good organic fertilizer/soil conditioner. Several operations have been successful whereas others have failed. There is ongoing interest in the use of black soldier flies to produce protein from RMP wastes.</p>  | Compost (N) | 8   | Medium/High     |
| <b>Surface Spreading</b>            | <p>Direct land application on the land surface. This method may be applied on the raw waste, or waste after stabilisation through composting or anaerobic digestion.</p> <p>Direct application of raw waste was widely used in the past due to low costs. However, this method is facing increasing regulations and</p>   |             | 9   |                 |

| Name                  | Description   | Products | TRL | RMP suitability |
|-----------------------|---|----------|-----|-----------------|
|                       | permitting requirements.  |          |     |                 |
| Sub-surface Injection | <p>Direct soil injection may be applied on the raw waste, or waste after stabilisation through composting or anaerobic digestion. This method involves mixing the waste within the soil layer and still requires EPA approval.</p> <p>This method is more expensive than surface spreading, but has the added advantage of reducing the fly problem but the long term effect on the soil should be monitored.</p> |          | 9   |                 |

Notes: E: energy recovery; N: nutrient recovery; V<sub>add</sub>: value-add product; GHG: greenhouse gases.

### 2.3.3 Resource Recovery – Alternative Value-add technologies

Table 4 provides further details on alternative value recovery technologies, including key products, technology readiness level (TRL – detailed in Appendix) and suitability for red meat processing applications. There are several emerging options for producing high protein feeds from waste, however much of the research is preliminary. The technology configuration and the technologies readiness is not clear for RMP applications, therefore production of animal feeds from organic waste has not been included in Table 4, but may be added to the final report.

**Table 4: Summary of Technologies used for Alternative Value-add Applications**

| Name         | Description   | Products                             | TRL | RMP suitability |
|--------------|---|--------------------------------------|-----|-----------------|
| Fermentation | <p>Partial-degradation of the waste by microorganisms to produce carboxylic acids.</p> <p>Low-tech low-cost technology. However, fermented waste generally requires further treatment before disposal.</p> <p>Fermented waste is compatible with AD and some thermal processing technologies.</p> <p>The carboxylic acids produced can be used as a carbon source for biological nutrient removal, converted to energy in anaerobic digester, converted to bioplastics or</p> | Carboxylic acids (V <sub>add</sub> ) | 5   | Medium/Low      |

| Name   | Description  | Products                             | TRL   | RMP suitability |
|--|--|--------------------------------------|---|-----------------|
|  | possibly sold as commodity chemicals.  |                                      |   |                 |
| <b>Wet Oxidation</b><br><br><b>(Baroutian et al. 2015, Bertanza et al. 2015)</b> | <p>Decomposition of waste at moderate temperature (150-350 °C) and high pressure (20-150 atm) using pure oxygen or air.</p> <p>Currently used to treat industrial wastewater with recalcitrant compounds.</p> <p>Pre-drying waste is not required.</p> <p>The carboxylic acids produced can be used as a carbon source for biological nutrient removal, converted to energy in anaerobic digester, converted to bioplastics or possibly sold as commodity chemicals.</p> <p>Although there are approx. 250 reference plants worldwide, there are still considerable knowledge gaps for RMP applications.</p> | Carboxylic acids (V <sub>add</sub> ) | 8-9   | Medium          |
| <b>Bioplastics</b>   | <p>Biological process that forces the accumulation of Polyhydroxyalkanoates (PHA) in bacterial cells. PHAs are used in the production of biodegradable bioplastics.</p> <p>Requires changing the STP operational conditions, including SS fermentation.</p> <p>Plastic yields are typically low and high recovery costs hinder process feasibility.</p> <p>After plastic recovery SS stills needs to be treated before disposal.</p> <p>Technology in its early stages.</p>  | Bioplastic (V <sub>add</sub> )       | 5   | Medium/Low      |
| <b>Fibre Extraction/ Biocomposites</b>   | <p>Sludge may be rich in undigested lignocellulose fibers. Such fibers could have value in making paper, board and biocomposite materials (applications including automotive, packaging, furnishings, decking, etc.).</p> <p>Fibres generally refined using chemical</p>   | Biocomposites (V <sub>add</sub> )    | Biocomposite – 9<br><br>Waste Application - 2 | Medium          |



| Name   | Description   | Products | TRL | RMP suitability            |
|--|---|----------|-----|----------------------------|
|  | digestion (K/NaOH)  |          |     |                            |
| <b>Rendering Primary effluent screenings</b> | Many RMP include primary treatment to separate waste high in fat, oil and grease. In some cases, the wastes can be recycled to rendering to produce lower grade tallow. However, depending on the primary treatment method, the by-products may be excluded rendered products from certain markets. |          | 9   | High (to FOG streams only) |

Notes: E: energy recovery; N: nutrient recovery; V<sub>add</sub>: value-add product; GHG: greenhouse gases.

### 3 PROJECT OBJECTIVES

- Conduct proof-of-concept testing (at laboratory scale) and identify the operational window of experimental parameters (moisture content of waste, airflow rate and sand-to-waste mass ratio) for robust self-sustaining smouldering and how these parameters impact the temperature and reaction kinetics of the process.
- Where appropriate, characterize the ash residues formed during the smouldering process, and assess the extent/potential for: i) odour generation/management; and ii) recovery of nutrient resources and value-add products.
- Develop a cost-benefit analysis of smouldering compared to other alternative low energy combustion approaches (and broader solid waste management technologies) appropriate for red meat industry application.
- Evaluate how the smouldering technology compares with: i) current best practice; and ii) emerging solid waste management strategies on an overall economic and environmental basis.
- Progress to preliminary field trials.

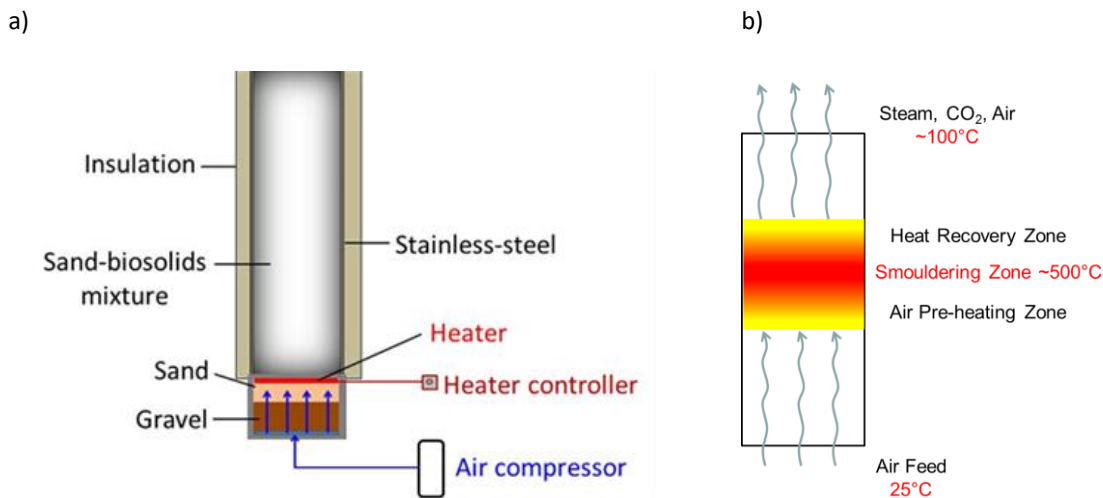
## 4 LOW TEMPERATURE SMOULDERING REVIEW

### 4.1 Summary

Smouldering combustion has emerged as an alternative treatment option for organic solid wastes with high moisture contents (80-85% wt), with some success in similar applications from other industries (Rashwan et al. 2016). The key advantage of the smouldering technology is that stable process performance can be achieved at very high moisture content without the need for external fuel and/or energy input. This key feature allows for treatment of problematic (high moisture, low caloric value) waste streams where alternate treatment methods (e.g. anaerobic digestion) are less attractive. A summary of the smouldering technology and the potential applications to red meat processing solid

wastes is given below:

- Smouldering is a slow, low-temperature combustion process that exhibits very high energy efficiency and therefore is able to treat solid wastes with high moisture content (~80% moisture) with virtually no external energy input (Rashwan et al. 2016).
- In the Smouldering process, wet solids (e.g. paunch, manure, DAF sludge) need to be embedded in a porous medium. Sometimes the fuel forms this porous medium but in other cases the wet solids are mixed with sand to create favorable reactor conditions. If sand is to be used, then the sand is recovered and recycled to the start of the process.
- A schematic representation of the smouldering reactor is illustrated in Schematic representation of the smouldering reactor. The reactor schematic is shown in (a); the operating concept is shown in (b).. Two key characteristics of smouldering enable this form of combustion to overcome the limitations of conventional incineration:
  - Smouldering combustion is controlled by oxygen diffusion to the fuel surface. Characteristic oxygen mass transfer time scales are comparable to heat transfer time scales within a porous medium (sand) resulting in a *very efficient heat exchange* between the reaction and the fuel.
  - Smouldering has a much lower activation energy than flaming combustion. This allows for the reaction to persist with much lower energy input than typical combustion.
- Smouldering can be applied to waste solids such as paunch, manure, DAF sludge, waste activated sludge and others. Smouldering can be applied to the wastes directly, or after these streams are treated using anaerobic digestion for energy recovery.
- The only solid residue from the process is inorganic ash, which dramatically reduces the mass of solid waste and further enables targeted recovery of valuable resources such as phosphate and coagulants, using state-of-the-art methods.
- Smouldering reactors achieve complete destruction of harmful pathogens.
- Smouldering reactors operate at ambient pressure – reducing the complexity and cost of process infrastructure.
- Smouldering reactors can operate as batch, continuous or even semi-continuous processes and are therefore well suited to slaughterhouse operations.



**Figure 3: Schematic representation of the smouldering reactor. The reactor schematic is shown in (a); the operating concept is shown in (b).**

## 4.2 Operating Principle

Smouldering combustion differs from other forms of combustion in that the reaction rates are much slower, with characteristic time scales consistent with diffusive processes. The slower reaction rates facilitate much more effective heat exchange thereby minimizing losses by radiation, conduction and convection. As a result chemical reactions associated with smouldering combustion are able to proceed at temperatures much lower than for other combustion processes.

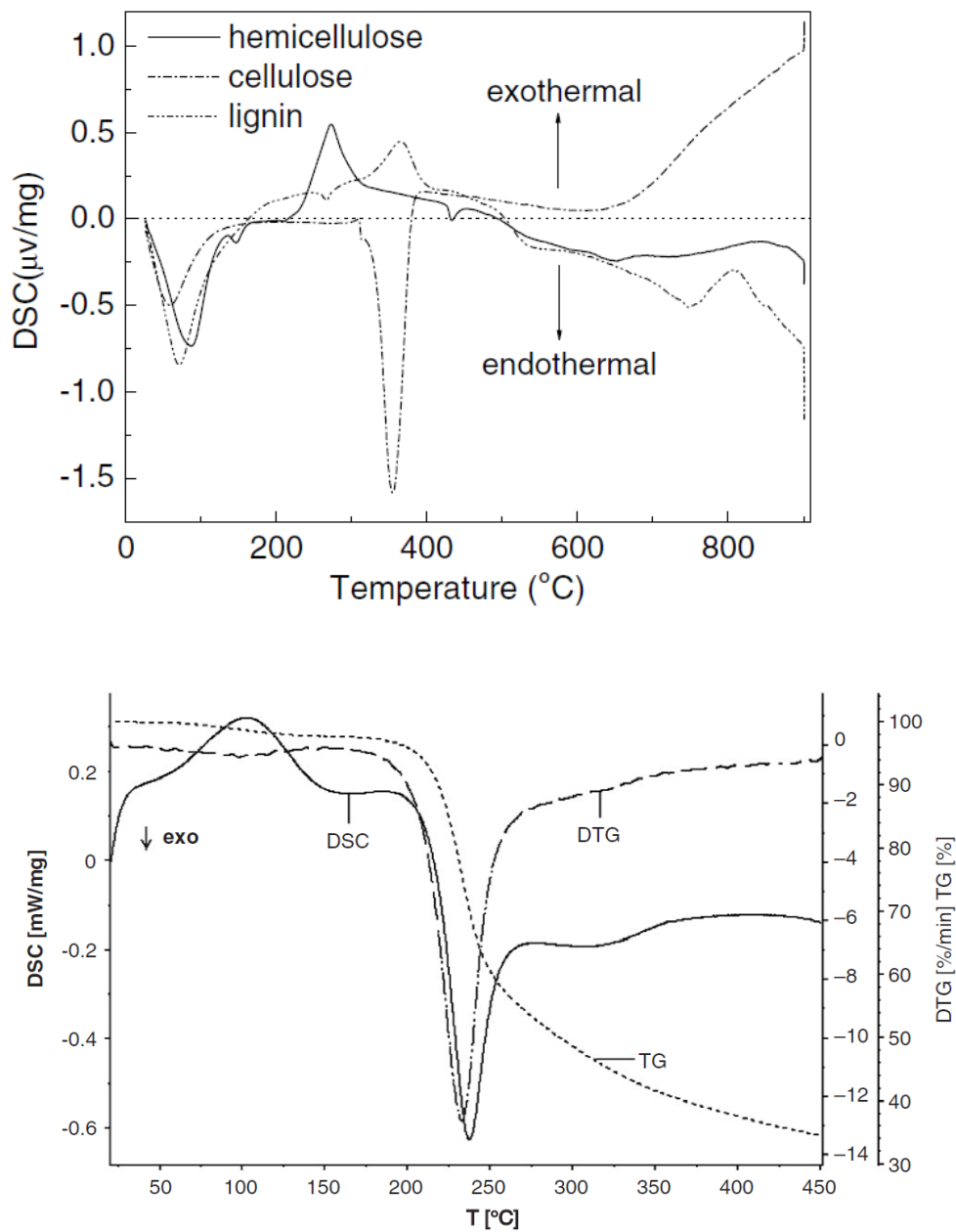
Research in the general area of smouldering provides detailed information on reaction rates and the transfer processes occurring in a smouldering process (Ohlemiller 1985, DiBlasi 1995, Leach *et al* 2000, Rein *et al* 2006, Hadden *et al* 2013, Huang and Rein 2014, Huang and Rein 2016(a), Yang *et al* 2015, Yang *et al* 2016). In general the reactions are similar to other forms of combustion, there is a mix of processes consuming heat energy (such as evaporation of water) and processes generating heat energy (pyrolysis and oxidative combustion of organics).

High moisture content generally means high demand from the energy consuming processes. For the energy generating reactions to occur, the heat energy provided by the combustion reactions (or an external heat source) must be sufficient to overcome the activation energy of the reactions. In traditional combustion processes, all energy generating and energy consuming reactions occur in the combustion flame. The flame thickness is very thin, so all chemical processes compete in the same location. Therefore, high moisture can cause quenching in traditional combustion processes.

While the chemical mechanisms associated to any combustion process are similar and apply to smouldering, the particular features of smouldering can result in an emissions profile that is very different to a conventional combustion or incineration. To understand smouldering emissions it is important to understand the different reactive stages of smouldering combustion. A unique feature of smouldering combustion is that the heat and mass transfer characteristics enable different reactions

to be spatially distributed (i.e. some physical separation between the energy consuming and energy generating reactions). When a porous medium is used within the smouldering reactor filtration and condensation processes are common. The result is a temporal evolution of emissions as the smouldering front progresses through the reactor. A review of most of the relevant literature shows that evaporation of relatively stable high molecular weight species occurs below about 220°C generating numerous products. Decomposition of biomass containing compounds such as starch, cellulose, hemicellulose, lignin, and pectin occurs mostly at temperatures higher than 220°C. As the temperature increases, thermal degradation of the lignocellulosic biomass will occur.

In a smouldering reactor, degradation of organics will occur through both pyrolysis and oxidative combustion and generally requiring a sequence of pyrolysis and oxidative combustion reactions occurring in different zones under different conditions. Pyrolysis is a complex process and can include both energy generating and energy consuming reactions. For the degradation process to become self-sustaining, the net energy generated by all reactions must surpass the apparent activation energy of all reactions combined. Temperature is a critical aspect of the process that impacts the degradation pathways. Tumuluru *et al* (2011) provides a detailed review of low temperature biomass degradation as part of a discussion on torrefaction. Figure 4 (extracted from Yang *et al* (2007) and Einhorn-Stoll *et al* (2007)) compares the degradation paths for hemicellulose, cellulose, lignin and pectin (typical components of biomass). While the onset of degradation for cellulose occurs above 300°C and is energy consuming (these processes will be referred here as endothermic pyrolysis), hemicellulose and pectin undergo energy producing degradation between 220°C and 250°C, lignin can undergo energy producing degradation as low as 150°C (exothermic). The composition of the gas products of degradation below 300°C are provided by Werner *et al* (2014) for different biomass products, showing the presence of CH<sub>4</sub>, CO and CO<sub>2</sub>. Pyrolysis reactions generally leave a char, which can be subsequently degraded through oxidative combustion at high temperature. Typical mass loss in the pyrolysis stage can reach approximately 10% of the biomass (Bergman *et al* (2005)). Figure 4 shows that below 300°C-350°C, endothermic pyrolysis reactions dominate over exothermic degradation reactions requiring an external heat supply to sustain the degradation of the material. At higher temperature, the exothermic degradation pathways are more dominant leading to excess heat, the goal is to transfer this excess heat through the porous media to support pyrolysis and pre-evaporate water away from the smouldering front.



**Figure 4: (top) DSC curves of hemicellulose, cellulose and lignin pyrolysis. (From Yang *et al* (2007)) (bottom) Thermal degradation of citrus pectin with DSC, TG and DTG curves (From Einhorn-Stoll *et al* (2007)).**

Complex heat and mass transfer processes will deliver the temperature distributions within a smouldering reaction. Establishing if the biomass has attained a sufficient temperature for self-sustained smouldering or smouldering propagation, requires accurate measurements of the temperature in the biomass and/or detailed modelling of all heat and mass transport processes as well as the decomposition chemistry (Ohlemiller 1985).

### 4.3 Incineration and the Formation of NO<sub>x</sub>

The temperatures achieved by flaming combustion (> 800°C) are much higher than the temperatures necessary for the onset of smouldering combustion (typically >350°C) and therefore emissions studies associated to incinerators will show drastic differences with those related to smouldering. A good example is the formation of NO<sub>x</sub>.

Gaseous emissions from combustion processes are mainly composed of carbon dioxide, oxygen, nitrogen and water but can also contain carbon monoxide, sulfur oxides, nitrogen oxides, hydrogen chloride and small quantities of dioxins and furans. The production of these unwanted compounds is related to the combustion process and the fuel. The fuel is generally a given parameter that can only be modified by means of separation and mechanical breakdown. Mechanical breakdown can affect the combustion process but the largest variability of the output is obtained by altering the operative conditions. Numerous studies have been developed to understand the influence of operating combustion parameters on the yield of pollutants and to better understand the mechanisms leading to their formation. Koshland (1996) and Lighty et al. (1998) provide in-depth reviews on these matters.

Different models have been developed to attempt adequately description of the behaviour of different waste incinerators. All of these models rely on strong simplifications. No consensus on an appropriate modelling methodology seems to exist, instead, modelling techniques have been chosen to best represent the characteristics of particular reactors. Nevertheless, what is clear is that the production of combustion products is all governed by what happens in the gas phase. Parameters such as excess air (i.e. global equivalence ratio), turbulence intensity and flame temperatures dominate over the outcome. Below 880°C the production of NO is very limited almost ceasing to exist at certain equivalence ratios. It is clear that under different burning conditions and reactor characteristics these values might vary but are not drastically different (Rogaume *et al* (2002 and 2004)).

It is possible that smouldering combustion of biomass reaches levels beyond the onset of NO<sub>x</sub> productions however, these temperatures have not been commonly attained with biomass or sludge (Rein *et al* (2009), Rashwan *et al* (2016), Yerman *et al* (2016)) and are more common with materials such coal tar (Kinsman *et al* (2017)). Most acceptable operating conditions will not exceed 900 K, thus self-sustained smouldering propagation can be maintained at temperatures below those that result in significant production of NO<sub>x</sub>.

### 4.4 Smouldering Emissions

The emissions from smouldering combustion are often far more numerous and complex with greater concentration yields than what is found in flaming combustion (Baker and Kilburn (1973), Muraleedharan *et al* (2000), Tissari *et al* (2008)). The emissions from smouldering are most strongly correlated to the chemical composition of the fuel. The chemistry of the fuel will be the strongest

determinant the possible gaseous and condensable thermal degradation products as well as the extent of fixed carbon remaining for combustion there-by also influencing combustion temperatures. The temperature affects the type of emissions produced but, in the case of smouldering, it is secondary to the importance of chemical structure. General emission products as a function of the starting fuel and smouldering region are shown in Table 5 and Table 6.

The spatial resolution of the different fronts associated to self-sustained smouldering propagation allows for a complex combination of compounds transferred with the flow from each stage of the degradation process. The spatial and temporal evolution of the smouldering front within the porous bed will determine the overall emissions of a reactor. Though it is well established that emissions from smouldering have multiple formation pathways, many smouldering experimental studies look at the bulk emissions for the global smouldering process and do not distinguish how or when they were formed. In contrast, extensive research has been carried out (primarily via TGA or Pyrolyser) to determine pyrolytic and oxidative thermal processes for many different chemical species with various reaction mechanisms proposed for the detected gaseous emissions. Important physical and chemical information can be elucidated from these studies, however, care must be taken when extrapolating these results to smoldering. Smouldering is a dynamic process where temperature and species concentrations can vary sharply over very small distances. Furthermore, heating rates in smouldering are dependent on the gaseous flux through the system and can also vary in space and time. Often, thermal degradation studies do not mimic the conditions as experienced in actual smouldering combustion by using unrepresentative heating rates and atmospheres (Baker (1987)).  $H_2$ , for example, is often a main pyrolytic decomposition product found in thermal degradation studies but is generally negligible in true smouldering because heating rates favours the formation of  $H_2O$ .



**Table 5: General emission products for different smouldering regions for biological fuels**

| Fuel Type                              | Boiling                 |                   | Distillation/Volatilization   |  | Exothermic Degradation   |   | Endothermic Pyrolysis  |  | High Temperature Oxidation  |  |
|--|-------------------------|-------------------|---|--|--|---|--|--|---|--|
|  | Inert Heating           |                   |   |  | Assisted Thermal Degradation   |   |  |  | Self-sustained Smouldering  |  |
| Biological Fuels (Biomass, Peat, etc.) | 20-100°C (Baker (1987)) |                   | 50-200°C (Baker (1987), Bertschi (2003))  |  | 100-350°C (Bertschi (2003), Baker (2006), Orfão <i>et al</i> (1999), Sharma <i>et al</i> (2001))   |   | 400-900°C (Baker (1987), Bertschi (2003), Baker (2006), Orfão <i>et al</i> (1999), Britt <i>et al</i> (2003))                                    |  | 500-950°C (Baker (2006), Olsson (2006), Baker and Kilburn (1973), Rein <i>et al</i> (2008), Bar-Ilan <i>et al</i> (2004), He <i>et al</i> (2014)) |  |
|  | Parent Compounds        | Emission Products | Parent Compounds  | Emission Products  | Parent Compounds   | Emission Products   | Parent Compounds   | Emission Products  | Parent Compounds  | Emission Products  |
|  | Bound Water             | Steam             | Terpenes (McKenzie (1996))[38], Light Hydrocarbons, Semi-Volatile Molecules (Baker and Bishop (2004)) | ~95% transmission through system (Baker and Bishop (2004)) | Cellulose (Baker 2006), Hemicellulose (Orfão <i>et al</i> (1999)), Lignin (Orfão <i>et al</i> (1999)), Sugars (Baker (1987), Pectin (Baker 1987), Sharma <i>et al</i> (2001)), Organic Acids, Long-Chain Hydrocarbons (Baker (2006)) | CO and CO <sub>2</sub> (Baker <i>et al</i> (2005), Baker and Kilburn (1973), Burton (1975), Baker <i>et al</i> (1981)), C <sub>1</sub> -C <sub>4</sub> Alkanes/Alkenes (Baker (1987), Baker <i>et al</i> (2005), Baker <i>et al</i> (1981), Orfão <i>et al</i> (1999)), Small Alcohols Ketones/Aldehydes (Formaldehyde)(Baker (1987), McKenzie <i>et al</i> (1984), Bertschi (2003), Yokelson <i>et al</i> (1997), Olsson (2006)), HCN (Lobert <i>et al</i> (1991)), NH <sub>3</sub> (Yokelson <i>et al</i> (1997)) | Cellulose, Lignin (Bertschi (2003)), Amino Acids (Baker (1987), Baker (2006)), Esters (Baker (1987)), Plant Steroids (Britt <i>et al</i> (2001)) | CO/CO <sub>2</sub> (Baker and Kilburn (1973), Baker <i>et al</i> (2005), Burton (1975), Baker (1981)), >C <sub>4</sub> Alkanes/Alkenes (Bertschi (2003), Baker (2006), Baker (1981)), Aromatic Hydrocarbons(Baker (2006), Olsson (2006)), PAHs (Britt <i>et al</i> (2003), Baker (2006), Britt <i>et al</i> (2004)), NH <sub>3</sub> , H <sub>2</sub> (Baker (1981)) | Fixed Carbon Chars, Bound Inorganics  | CO <sub>2</sub> , CO, PAHs (Black <i>et al</i> (2016), Robb <i>et al</i> (1966)), NO <sub>x</sub> , PCDD/F <sup>2</sup> (Black <i>et al</i> (2016)), H <sub>2</sub> O, HCN, (Alcohols and Ketones) |

- 1) This temperature region overlaps with the combustion region and can typically only occur in oxygen devoid regions around the combustion zone
- 2) Only possible with chlorinated species in the system
- 3) Hydrocarbon emissions emit broadly with little work exploring high temperature pyrolysis because it is either dominated by combustion or mineral decomposition
- 4) Decreasing yield with increasing chain length
- 5) Wide variety in peak temperature depending on fuel type, inherent moisture content, oxygen flux, and heat losses
- 6) Unlikely to initially have moisture content but some could form from combustion and condense in the system







**Table 6: General emission products for different smouldering regions for heavy hydrocarbon, tars and sludge fuels**

| Fuel Type                            | Boiling          |                   | Distillation/Volatilization  |                   | Exothermic Degradation  |  | Endothermic Pyrolysis   |  | High Temperature Oxidation   |   |  |  |
|--------------------------------------|------------------|-------------------|--|-------------------|---|--|---|--|--|---|--|--|
|                                      | Inert Heating    |                   |  |                   | Assisted Thermal Degradation  |  |   |  | Self-sustained Smouldering   |   |  |  |
| Heavy Hydrocarbon Tars/Sludges/Shale | 20-100°C         |                   | 50-250°C   |                   | 200-600°C <sup>3</sup> (Karayildrim <i>et al</i> (2006), Xu and Huang (2010), Tiwari and Deo (2012), Huang <i>et al</i> (2016))                                     |  |   |  | 500-1200°C <sup>5</sup> (Xu and Huang (2010), Switzer <i>et al</i> (2014), Martins <i>et al</i> (2010(b))) |   |  |  |
|                                      | Parent Compounds | Emission Products | Parent Compounds   | Emission Products | Parent Compounds  |  | Emission Products   |  | Parent Compounds   | Emission Products   |  |  |
|                                      | Bound Water      | Steam             | Volatile aliphatic and aromatic compounds, Saturates (Xu and Huang (2010)) |                   | Long-Chain Saturated and Unsaturated Hydrocarbons (Karayildrim <i>et al</i> (2006)), Aromatic and Naphthalenes, Asphaltenes (Xu and Huang (2010)), Bitumen, Kerogen |  | CO/CO <sub>2</sub> , C <sub>1</sub> -C <sub>8</sub> Alkanes/Alkenes/Alkynes <sup>4</sup> (Karayildrim <i>et al</i> (2006), Tiwari and Deo (2012), Pan <i>et al</i> (2015)), Aromatic Hydrocarbons (Karayildrim <i>et al</i> (2006), Xu and Huang (2010), Pan <i>et al</i> (2015)), PAHs, SO <sub>2</sub> (Martins <i>et al</i> (2010 (a)))[48], H <sub>2</sub> (Huang <i>et al</i> (2016), Monhol and Martins (2015)) |  | Fixed Carbon, Char, O <sub>2</sub> , Bound Inorganics  | CO <sub>2</sub> , CO, PAHs, NO <sub>x</sub> [20], PCCD/F <sup>2</sup> , H <sub>2</sub> O, Formic/ Naphthenic Acids, Aromatic Hydrocarbons (Xu and Huang (2010)) |  |  |

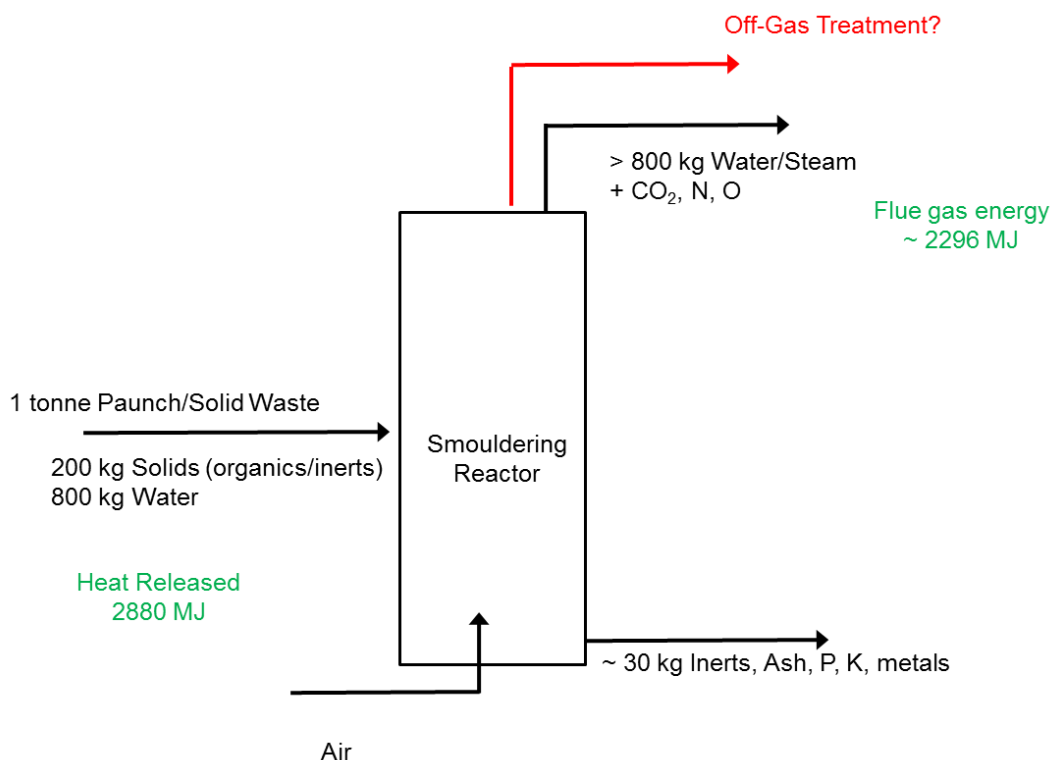
- 1) This temperature region overlaps with the combustion region and can typically only occur in oxygen devoid regions around the combustion zone
- 2) Only possible with chlorinated species in the system
- 3) Hydrocarbon emissions emit broadly with little work exploring high temperature pyrolysis because it is either dominated by combustion or mineral decomposition
- 4) Decreasing yield with increasing chain length
- 5) Wide variety in peak temperature depending on fuel type, inherent moisture content, oxygen flux, and heat losses
- 6) Unlikely to initially have moisture content but some could form from combustion and condense in the system



## 4.5 Application to the Red Meat Industry

As a stand-alone technology, smouldering is able to deliver value through complete dewatering combined with significant reduction in waste solids mass and volume. The most useful comparison in literature is the treatment of dewatered biosolid from municipal wastewater treatment, this is a low energy organic waste with challenging dewatering properties and a stream where smouldering was successful at up to 80% moisture (Rashwan et al. 2016).

The specific operating conditions for successful smouldering will depend on the process conditions and the energy content of the waste. Importantly, the energy available from combustion must exceed the energy required for evaporation of water combined with any losses occurred from inefficient mass and energy transfer. An example energy balances using manure is shown in Figure 5. The example energy balance is based on a smouldering feed of cattle paunch at 80% moisture. Cattle paunch was selected for the example due to the high production and high disposal costs at many RMP. The energy balance suggests that the combustion energy in paunch is more than sufficient to completely evaporate the embedded water, however actual performance will vary depending on the combustion efficiency and losses.



**Figure 5: Preliminary energy balance on a smouldering process with paunch solid waste as the process feed (assuming calorific value for paunch of 17 kJ/dry kg and 85% recovery of this energy).**

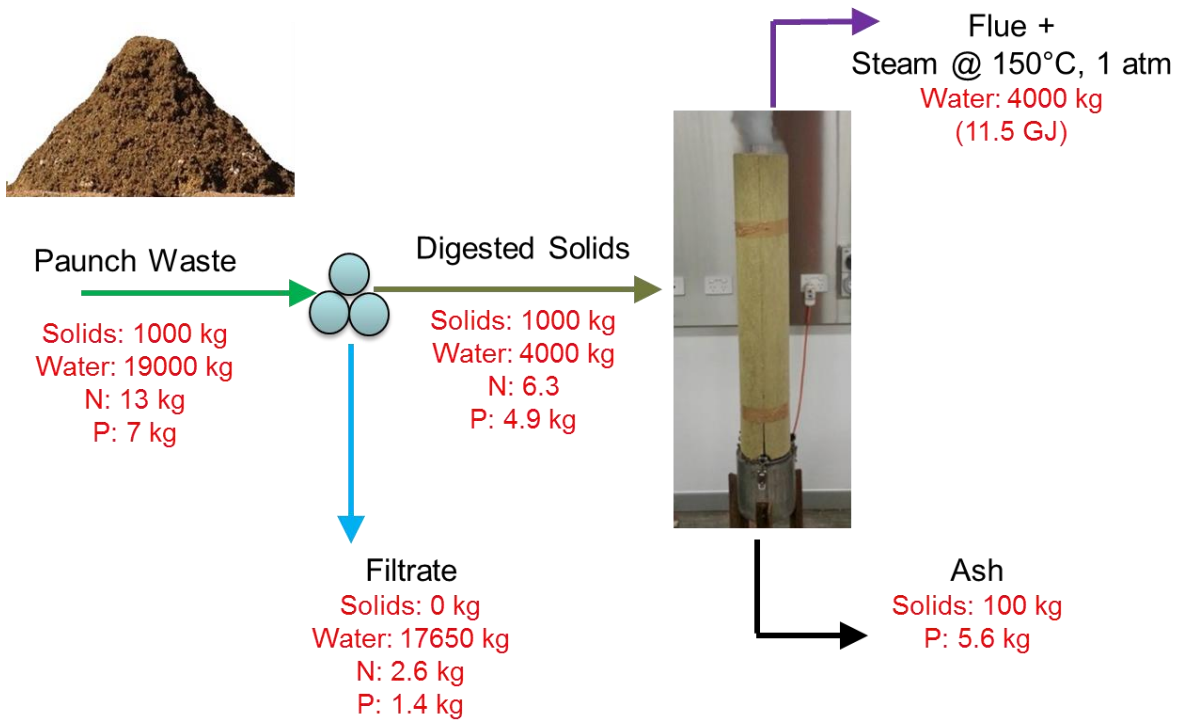
As a guide, smouldering has the capacity to reduce 1 ton of dewatered meat processing solid organic

waste (moisture content 80% wt and organic solids at 90% of dry matter) to approximately 20-30 kg of ash, without the need for external fuel or heat input. However, the specific benefits of smouldering will vary for each stream based on the moisture content and the ash content. Examples of RMP solid wastes where smouldering may be applied are shown in Table 7, with the exception of Saveall sediment all the solid wastes are <80% moisture. The ash content of the waste represents the final mass expected after application of smouldering. For the wastes in Table 7, mass reductions ranging from 99% for paunch to 75% for manure would be expected.

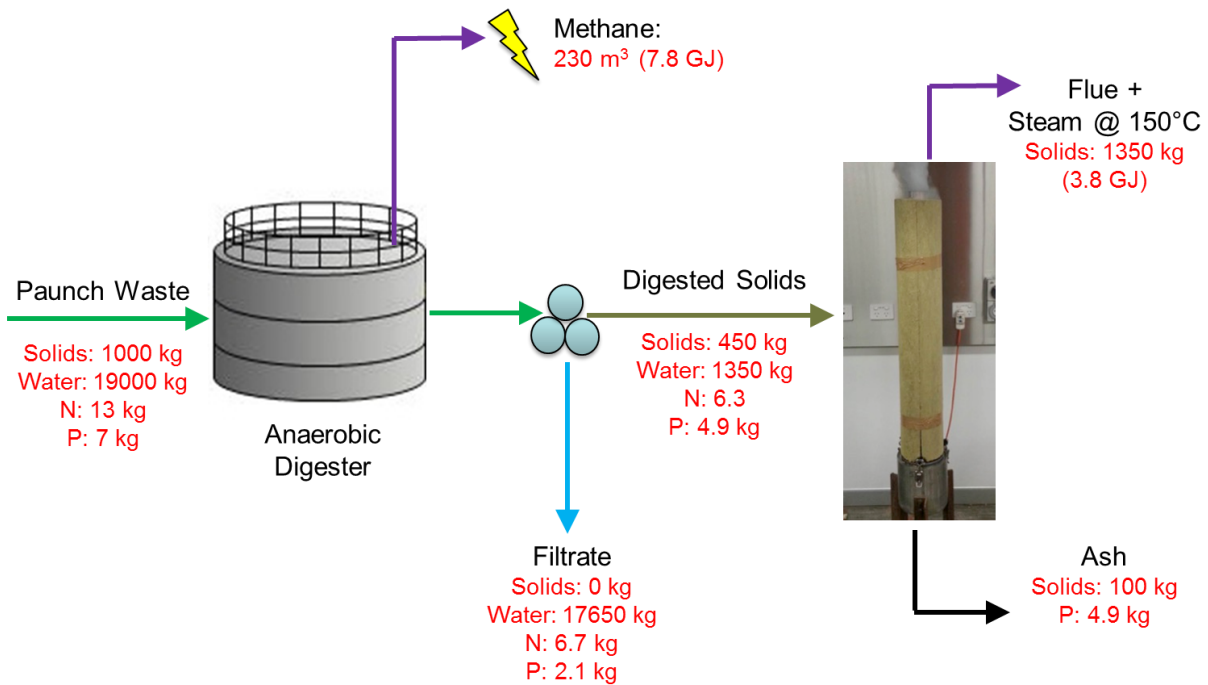
**Table 7: Example Compositions of Solid Waste at Australian RMP (2017/1031)**

| Sample type                          | Mixed Species Paunch | Cattle Manure  | Sheep Manure    | Saveall sediment | Tallow (saveall float) | DAF float      |
|--------------------------------------|----------------------|----------------|-----------------|------------------|------------------------|----------------|
| TS (g/kg)                            | 229 ± 5              | 558 ± 54       | 385 ± 25        | 144 ± 12         | 237 ± 30               | 620 ± 10       |
| VS (g/kg)                            | 220 ± 4              | 314 ± 36       | 283 ± 20        | 108 ± 12         | 228 ± 29               | 594 ± 13       |
| <b>Ash (g/kg)</b>                    | <b>9 ± 5</b>         | <b>244 ± 5</b> | <b>102 ± 30</b> | <b>36 ± 18</b>   | <b>109 ± 35</b>        | <b>26 ± 16</b> |
| VS/TS                                | 0.96 ± 0.03          | 0.56 ± 0.15    | 0.73 ± 0.09     | 0.75 ± 0.14      | 0.96 ± 0.18            | 0.96 ± 0.03    |
| Total COD (gO <sub>2</sub> /kg)      | 249 ± 23             | 364 ± 22       | 339 ± 36        | 184 ± 5          | 473 ± 37               | 1,081 ± 105    |
| TCOD/VS                              | 1.14 ± 0.09          | 1.16 ± 0.13    | 1.2 ± 0.13      | 1.7 ± 0.12       | 2.08 ± 0.15            | 1.82 ± 0.1     |
|                                      |                      |                |                 |                  |                        |                |
| Total TKN (mgN/kg)                   | 3,507                | 13,533         | 10,447          | 2,781            | 1146                   | 5295           |
| Soluble TKN (mgN/kg)                 | 41                   | 245            | 1369            | 179              | 39                     | 44             |
| NH <sub>4</sub> <sup>+</sup> (mgN/L) | 36                   | 194            | 1,278           | 113              | 5                      | 17             |
| Total TKP (mgP/kg)                   | 260                  | 6334           | 2385            | 551              | 618                    | 2841           |
| Soluble TKP (mgP/kg)                 | 14                   | 120            | 35              | 91               | 73                     | 22             |
| PO <sub>4</sub> -P (mgP/L)           | 68                   | 461            | 37              | 95               | 88                     | 84             |
|                                      |                      |                |                 |                  |                        |                |
| Aluminium (Al) (mg/kg)               | 17                   | 607            | 399             | 109              | 20                     | 156            |
| Calcium (Ca) (mg/kg)                 | 2,587                | 9,220          | 6,544           | 2,870            | 3,231                  | 11,807         |
| Iron (Fe) (mg/kg)                    | 62                   | 820            | 665             | 244              | 106                    | 426            |
| Potassium (K) (mg/kg)                | 104                  | 9,637          | 6,934           | 106              | 76                     | 234            |
| Magnesium (Mg) (mg/kg)               | 156                  | 2,386          | 1,092           | 291              | 60                     | 151            |
| Sodium (Na) (mg/kg)                  | 270                  | 4,507          | 6,061           | 193              | 211                    | 210            |
| Sulfur (S) (mg/kg)                   | 307                  | 1,844          | 1,730           | 185              | 160                    | 540            |

Importantly, smouldering can be applied to these wastes directly, or after application of energy recovery technologies such as Anaerobic Digestion. Example mass and energy balances for different process implementations are shown in Figure 6 and Figure 7. The use of anaerobic digestion as a smouldering pre-treatment will not impact the final solids for disposal, however AD may improve paunch dewatering and facilitate energy recovery in the order of 8GJ/dry ton paunch.



**Figure 6: Example mass and energy balance for smouldering applied to dewatered paunch**



**Figure 7: Example mass and energy balance for smouldering applied to dewatered paunch after anaerobic digestion**

## 5 METHODOLOGY

### 5.1 Stage 1: Desktop analysis and basic feasibility

- Conduct complete literature review, including competitive analysis against pyrolysis, torrefaction, combustion (e.g. boiler fuel), incineration, anaerobic digestion and composting. As well as cost benefit analysis, value proposition, and SWOT analysis of the technology.
- This will complete 3 months after the project start, and will represent a stop/go point with the following criteria:
  - Capital cost estimates are order of magnitude comparable with existing platforms (e.g. composting, digestion, combustion).
  - Return on investment for a range of product utilisation options comparable with existing processes (i.e., >10% ROI).

### 5.2 Stage 2: Technical feasibility through batch testing

Stage 2 aims to demonstrate proof-of-concept and gain an in-depth understanding of the operational boundaries and optimal process conditions to maintain self-sustainable smouldering conditions (conditions without external heat or fuel supply). This will provide essential support for the design and operation of a continuous process and/or a pilot-scale facility proposed in Stage 3 (to be submitted for funding review in 2017/18). Of particular importance will be to establish if an inert solid (i.e. sand) is necessary for the smouldering reaction to be self-sustained.

The most important parameter for assessment in the bench top testing is determination of the maximum water content where smouldering combustion is self-sustaining. This assessment must also consider the variability of organic waste composition and possible impacts on the calorific value. Therefore, extensive experimental investigations will be conducted using a smouldering reactor operating in batch-mode. Key operational parameters that will be investigated will be:

- (i) **Origin of the organic waste (paunch, manure, DAF sludge, wastewater treatment sludge)**
- (ii) **Moisture content of the waste,**
- (iii) **Sand-to-waste mass ratio (if sand is required to create a porous media), and**
- (iv) **Air flow.**

Bench-scale experiments (20 L) under different conditions will determine the operational window for self-sustaining smouldering as a function of moisture content, sand-to-waste ratio and air flow. The experiments allow accurate assessments on the impact of the above mentioned key parameters on the overall process performance in terms of temperature and organics removal/dewatering rate.

### **5.3 Stage 3: Development of a continuous process and dynamic field testing**

Based on the outcomes of the batch experiments, continuous tests will be conducted to determine long-term process performance. The continuous reactor operates in a plug-flow style. The process design includes a turntable at the bottom that allows for continuous (or intermittent) sand removal, while fresh sand-waste mixture is added from the top. The removal rates are designed to maintain the smouldering front at a constant height in the reactor. In the continuous experiments the temperatures at different reactor heights will be measured in real-time by means of thermocouples placed along the axis of the reactor. The temperature histories obtained from these measurements will be used to determine the organics removal/dewatering rate.

Multi-criteria assessment (MCA) will be used for a detailed assessment of the relative merits of smouldering technology, compared to current best practice solid management (and other emerging technologies) in the red meat processing industry. This will include a thorough cost estimate generated based on the results of initial batch testing and updated through long-term pilot testing. This will be compared against the current economic cost for waste management in red meat processing and may include broader industry comparison such as Australian water utilities in Australia. A risk assessment will be used to determine the OH&S implications of the proposed technology.

## **6 SMOULDERING LABORATORY RESULTS**

### **6.1 Paunch Sample Collection**

Paunch samples were collected from 2 QLD red meat processing facilities for analysis in this project, named Site A and Site B. Samples differed on animal breed, diet and dewatering method.

Paunch samples were characterized by the following techniques:

- Moisture, ash and volatile matter content (proximate analysis)
- Elemental analysis: basic chemical composition (C, H, N, S, O, P and metals)
- Energy content (gross heat of combustion)
- Thermo-gravimetric analysis (TGA): to understand the reactions taking place during smouldering. Gives information on the ignition temperature.

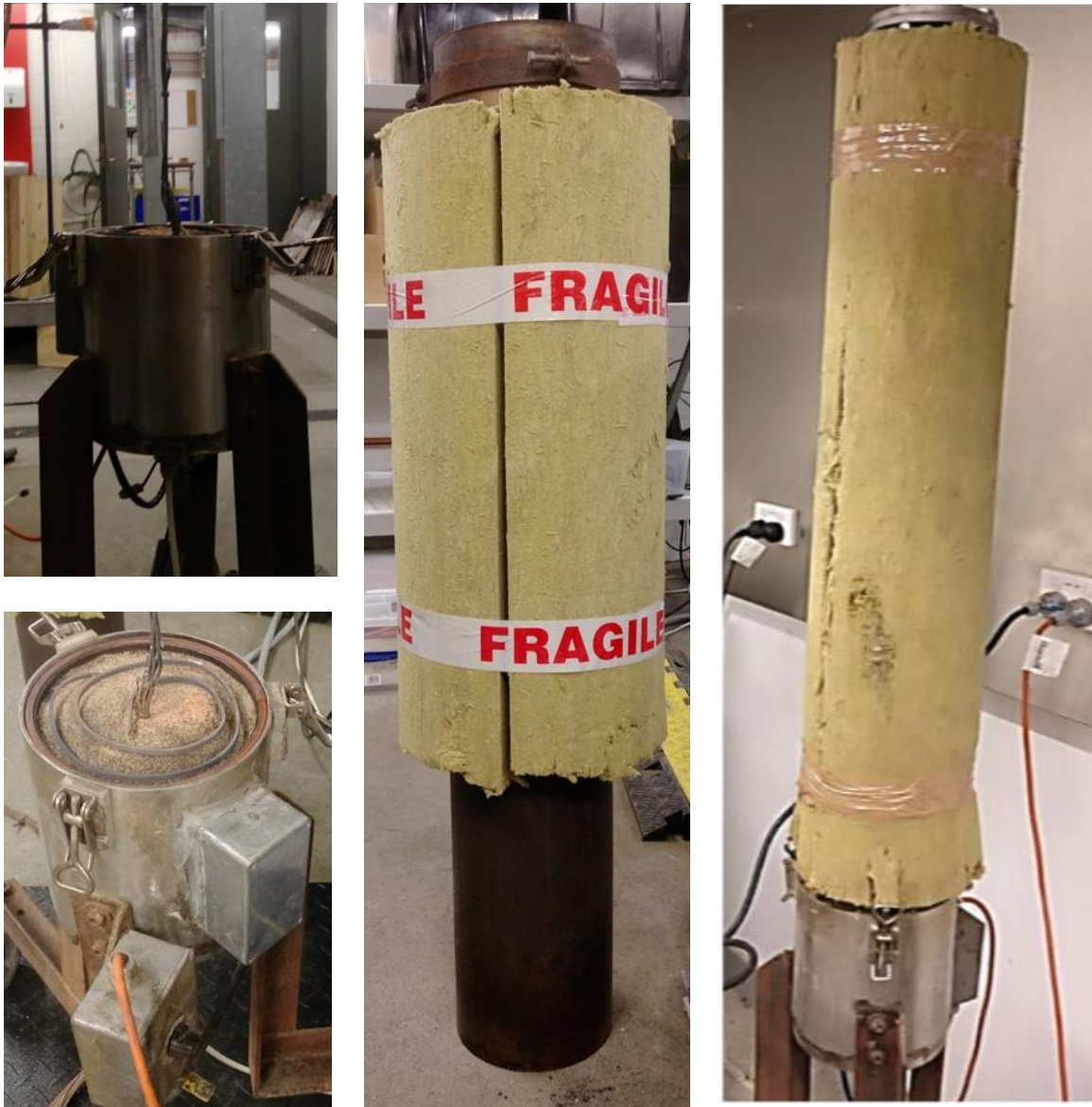


**Figure 8: Site B paunch grass mixed with sand**

## **6.2 Experimental set-up**

Smouldering experiments were carried out in a column reactor (0.16 m internal diameter and 1 m height). Key components of the reactor are shown in Figure 9.

A series of batch experiments were performed in order to assess the impact of moisture content, airflow, sand/waste ratio on smouldering performance. During each batch experiment, the bottom layer of the column was initially heated until the temperature reached 200°C. When the bottom of the waste bed reached 200°C, airflow was initiated and external heating turned off. The reactor then relies on self-sustaining combustion to complete the smouldering process.



**Figure 9: Main constitutive parts of smouldering reactor. Top left: base showing air inlet below and thermocouple tree above. Bottom left: electric coil heater. Middle: stainless steel column and Rockwool® insulation. Right: The assembled reactor**

## 6.3 Results

### 6.3.1 Paunch characterization

Paunch samples collected from each site for were characterized by the following techniques:

- Moisture, ash and volatile matter content (proximate analysis)
- Elemental analysis: basic chemical composition (C, H, N, S, O, P and metals)



- Energy content (gross heat of combustion)
- Thermo-gravimetric analysis (TGA): to understand the reactions taking place during smouldering. Gives information on the ignition temperature.

The results are summarized in Table 8 to Table 10. Paunch from Site A contained a lower solids content and a lower fraction of organic matter than paunch from Site B, contributing to a lower calorific value (16.9 kJ/dry kg compared to 17.6 kJ/dry kg), it is therefore expected that paunch from Site A will be more challenging to achieve self-sustaining-smouldering.

**Table 8: Paunch composition from Site A and Site B – Solids, moisture, energy content**

|                            | Site A | Site B |
|----------------------------|--------|--------|
| Dry Matter (% wet basis)   | 17     | 23     |
| Moisture (% wet basis)     | 83     | 77     |
| Volatiles (% dry basis)    | 72.2   | 84.6   |
| Fixed carbon (% dry basis) | 18.5   | 5.9    |
| Ash (% dry basis)          | 9.4    | 9.5    |
| Energy (kJ/g, dry basis)   | 16.9   | 17.6   |

**Table 9: Paunch composition from Site A and Site B – non-metallic elements (dry basis)**

| Paunch | C<br>g.kg <sup>-1</sup> | H<br>g.kg <sup>-1</sup> | N<br>g.kg <sup>-1</sup> | S<br>g.kg <sup>-1</sup> | O<br>g.kg <sup>-1</sup> | P<br>g.kg <sup>-1</sup> | B<br>g.kg <sup>-1</sup> |
|--------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| Site A | 40.8                    | 5.3                     | 1.3                     | 0.2                     | 48.0                    | 0.7                     | < 0.1                   |
| Site B | 44.0                    | 5.8                     | 1.5                     | 0.1                     | 47.2                    | 0.4                     | < 0.1                   |

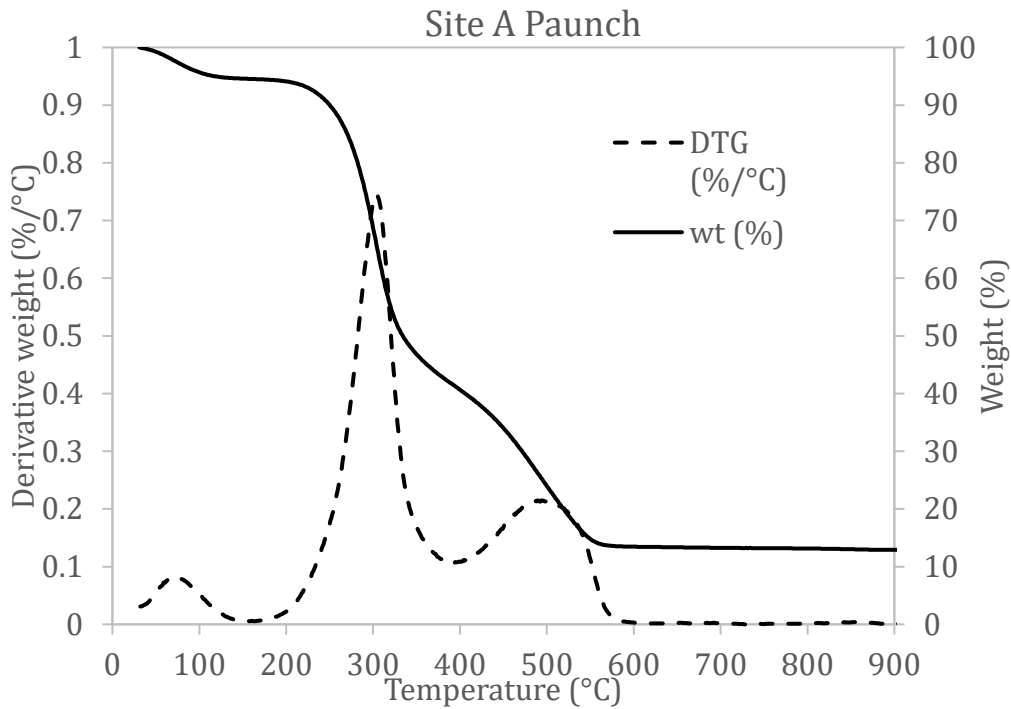
**Table 10: Paunch composition from Site A and Site B – metallic elements (dry basis)**

| Paunch | Al<br>mg.kg <sup>-1</sup> | Ca<br>mg.kg <sup>-1</sup> | Cu<br>mg.kg <sup>-1</sup> | Fe<br>mg.kg <sup>-1</sup> | K<br>mg.kg <sup>-1</sup> | Mg<br>mg.kg <sup>-1</sup> | Na<br>mg.kg <sup>-1</sup> | Zn<br>mg.kg <sup>-1</sup> |
|--------|---------------------------|---------------------------|---------------------------|---------------------------|--------------------------|---------------------------|---------------------------|---------------------------|
| Site A | 720                       | 7285                      | 9.2                       | 9.0                       | 1051                     | 3424                      | 2496                      | 43                        |
| Site B | 135                       | 4328                      | 6.9                       | 11.9                      | 367                      | 1423                      | 3175                      | 129                       |

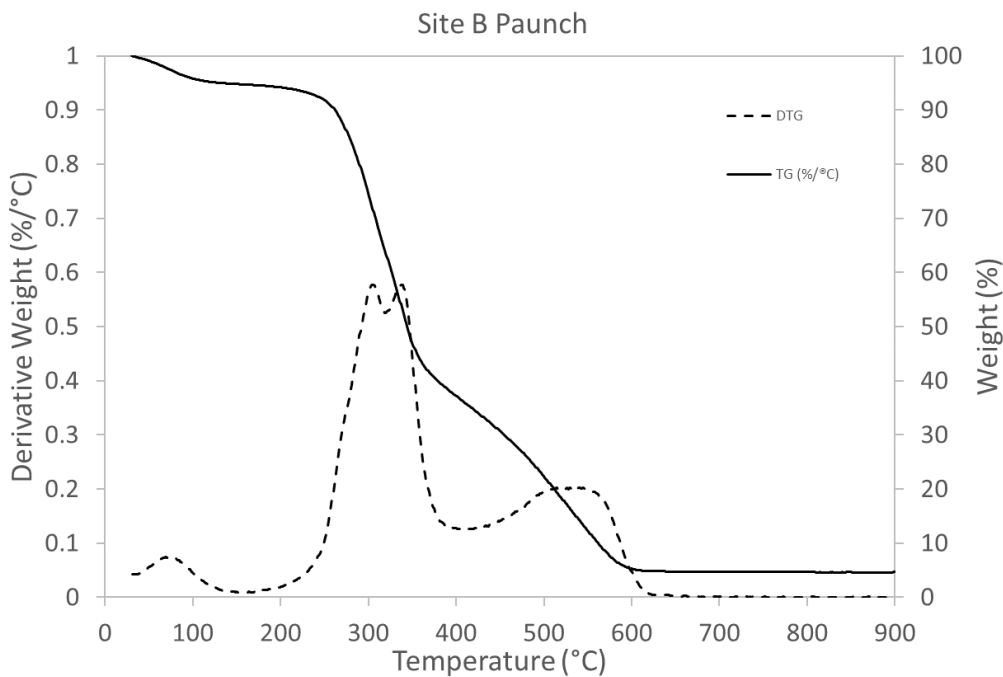
Thermo-gravimetric analysis (TGA) is used to assess the chemical reactions taking place during the smouldering process. TGA experiments were conducted using air as the atmosphere and at a heating rate of 20°C per minute. The TGA profiles from Site A and Site B are shown in Figure 10 and Figure 12 respectively. The paunch samples from both sites showed similar TGA profiles indicating no significant differences in the combustion behavior.

Results showed paunch from Site A was combusted between approximately 200 and 580 °C, while paunch from Site B was combusted between 200 and 610 °C. These paunch combustion profile are similar to the combustion profiles of cellulose and hemicellulose (between 200 and 400 °C) and lignin (between 400 and 600 °C), this finding is consistent with the high lignocellulosic content expected for

paunch. Combustion temperatures of at least 400 °C are expected during smouldering, necessary to burn the lignin present in the paunch grass. Based on these results, an ignition temperature of 250°C was chosen according to the results and previous knowledge on smouldering.



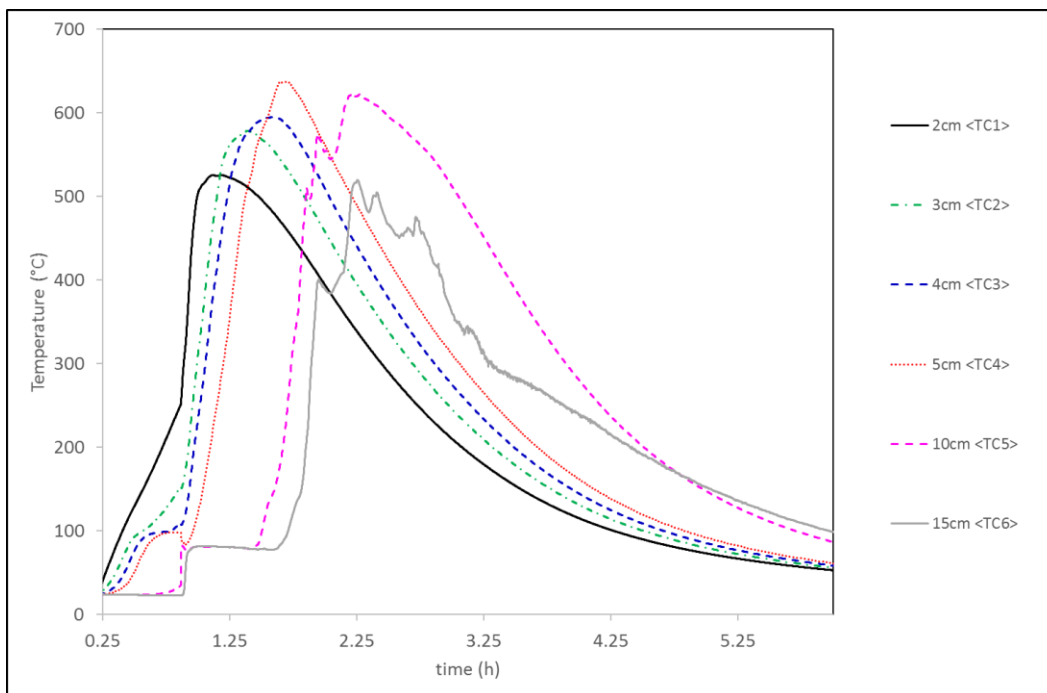
**Figure 10: Combustion profile of paunch from Site A – from TGA**



**Figure 11: Combustion profile of paunch from Site B – from TGA**

### 6.3.2 Smouldering experiments

Batch smouldering experiments were performed using 18 different process conditions in order to assess the impact of moisture content, airflow, sand/waste ratio on smouldering performance. An example of the temperature histories for a SSS experiment is shown in Figure 12, key data points from the experiments are shown in Table 11 to Table 15.



**Figure 12: Example of the temperature histories from a SSS experiment of paunch grass**

When self-sustaining smouldering (SSS) is achieved, all waste is burned and only ash and sand remain inside the reactor. When self-sustaining smouldering is not achieved (i.e. the reaction quenches), a crust of char and unburned waste remain inside the reactor along with the sand (see Figure 13). The goal of the lab testing is to achieve self-sustaining smouldering.



**Figure 13: Ash and sand at the end of a self-sustaining experiment (left). Char and unburned waste at the end of a non-self-sustaining experiment (right)**

Minimum solids content to achieve self-sustaining -smouldering

The impact of moisture content was assessed using a fixed airflow rate of 10 cm/s (2 L/s) and sand/paunch mass ratio of 2. Key results are presented in Table 11. The results presented in Table 11 are the average of replicate experiments under each condition. Results demonstrate that self-sustaining smouldering is achieved at a paunch solids content of 25%.

**Table 11: Key outcomes from smouldering experiments assessing impact of moisture content**

| Experiment | Moisture (%) | Self-Sustaining | Maximum temperature (°C) | Average temperature (°C) | Paunch destruction rate (g/min) |
|------------|--------------|-----------------|--------------------------|--------------------------|---------------------------------|
| 1          | 80           | NO              | 556                      | 326                      | -                               |
| 2          | 75           | YES             | 718                      | 402                      | 23                              |
| 3          | 70           | YES             | 761                      | 420                      | 20                              |
| 4          | 65           | YES             | 1049                     | 453                      | 14                              |

Minimum airflow to achieve self-sustaining -smouldering

The impact of air flowrate was assessed using a fixed moisture content of 70% and a sand/paunch mass ratio of 2. Key results are presented in Table 12. The results presented in Table 12 are the average of

replicate experiments under each condition. Results demonstrate that self-sustaining smouldering is achieved at a lower air flowrate of 1 cm/s (0.2 L/s). Reaction rates were increased with higher air flowrates.

**Table 12: Key outcomes from smouldering experiments assessing impact of airflow rate**

| Experiment | Air flowrate (cm/s) | Self-Sustaining | Maximum temperature (°C) | Average temperature (°C) | Paunch destruction rate (g/min) |
|------------|---------------------|-----------------|--------------------------|--------------------------|---------------------------------|
| 5          | 0.5                 | NO              | 505                      | 374                      | -                               |
| 6          | 1                   | YES             | 644                      | 410                      | 7                               |
| 7          | 2                   | YES             | 752                      | 454                      | 8                               |
| 8          | 4                   | YES             | 719                      | 447                      | 11                              |
| 9          | 10                  | YES             | 761                      | 420                      | 20                              |

Minimum sand-to-waste ratio to achieve self-sustaining -smouldering

The impact of sand/paunch mass ratio was assessed using a fixed moisture content of 70% and air flowrate of 1.2 cm/s. Key results are presented in Table 13. The results presented in Table 13 are the average of replicate experiments under each condition. Results demonstrate that self-sustaining smouldering can be achieved without the addition of sand as a porous medium to support combustion.

The temperatures are considerable higher (900 vs 600-700 C). Further research is needed to determine the potential impact of these differences in temperature on the composition of the flue gas and subsequent flue gas treatment requirements.

**Table 13: Key outcomes from smouldering experiments assessing impact of sand-to-waste ratio**

| Experiment | Sand-to-waste ratio | Self-Sustaining | Maximum temperature (°C) | Average temperature (°C) | Paunch destruction rate (g/min) |
|------------|---------------------|-----------------|--------------------------|--------------------------|---------------------------------|
| 10         | 0                   | YES             | 902                      | 517                      | 8                               |
| 11         | 1                   | YES             | 678                      | 447                      | 6                               |
| 12         | 2                   | YES             | 644                      | 462                      | 8                               |

Minimum solids content to achieve self-sustaining –smouldering (without addition of sand)

The impact of moisture content was assessed using a fixed airflow rate of 1.2 cm/s (0.24 L/s). Key results are presented in Table 14. The results demonstrate that the **moisture content for self-sustaining smouldering cannot be increased when sand is not used.**

**Table 14: Key outcomes from smouldering experiments assessing moisture content without adding sand as a porous medium to support combustion**

| Experiment | Moisture (%) | Self-Sustaining | Maximum temperature (°C) | Average temperature (°C) | Paunch destruction rate (g/min) |
|------------|--------------|-----------------|--------------------------|--------------------------|---------------------------------|
| 13         | 70           | YES             | 902                      | 517                      | 8                               |
| 14         | 77           | NO              | 526                      | 354                      | -                               |

#### Minimum airflow to achieve self-sustaining –smouldering with addition of sand

The impact of air flowrate on smouldering performance without the addition of sand was assessed using a fixed moisture content of 70%. Key results are presented in Table 15. The results presented in Table 15 are the average of replicate experiments under each condition. Results demonstrate that self-sustaining smouldering is achieved at a lower air flowrate of 1.2 cm/s (0.24 L/s). As the air flowrate increases the destruction rate increases in a near linear relationship, however the reaction temperatures remain approximately constant.

**Table 15: Key outcomes from smouldering experiments airflow without adding sand as a porous medium to support combustion**

| Experiment | Air flowrate (cm/s) | Self-Sustaining | Maximum temperature (°C) | Average temperature (°C) | Paunch destruction rate (g/min) |
|------------|---------------------|-----------------|--------------------------|--------------------------|---------------------------------|
| 15         | 0.5                 | NO              | 837                      | 453                      | -                               |
| 16         | 1.2                 | YES             | 902                      | 517                      | 8                               |
| 17         | 2                   | YES             | 838                      | 501                      | 20                              |
| 18         | 5                   | YES             | 905                      | 526                      | 27                              |

## 6.4 Summary of Outcomes

- Self-sustaining smouldering of paunch can be achieved at small-scale without the addition of a porous sand medium, this may reduce the complexity of plant design and operation (i.e. no required to mix paunch and sand before smouldering and no requirement to

separate ash and sand after smouldering.

- Results showed that the limits for moisture content and air flowrate are 75% and 1 cm/s, respectively. This result demonstrates that smouldering could be applied to many RMP using paunch processing with currently used dewatering technologies, no addition pre-drying is required. Small scale laboratory experiments are less efficient than large scale reactors, therefore these results are expected to be conservative and further improvements are expected.
- The maximum smouldering temperature increases when the moisture content is decreased, reaching over 1000 °C at 65% moisture. However, the destruction rate decreases. Higher temperatures may increase the risk of NO<sub>x</sub> in the flue gas.
- The maximum smouldering temperature increases in a near linear relationship when air flowrate increases. However, the impact on the temperature can be neglected.

## **7 DEVELOPMENT OF SMOULDERING PILOT**

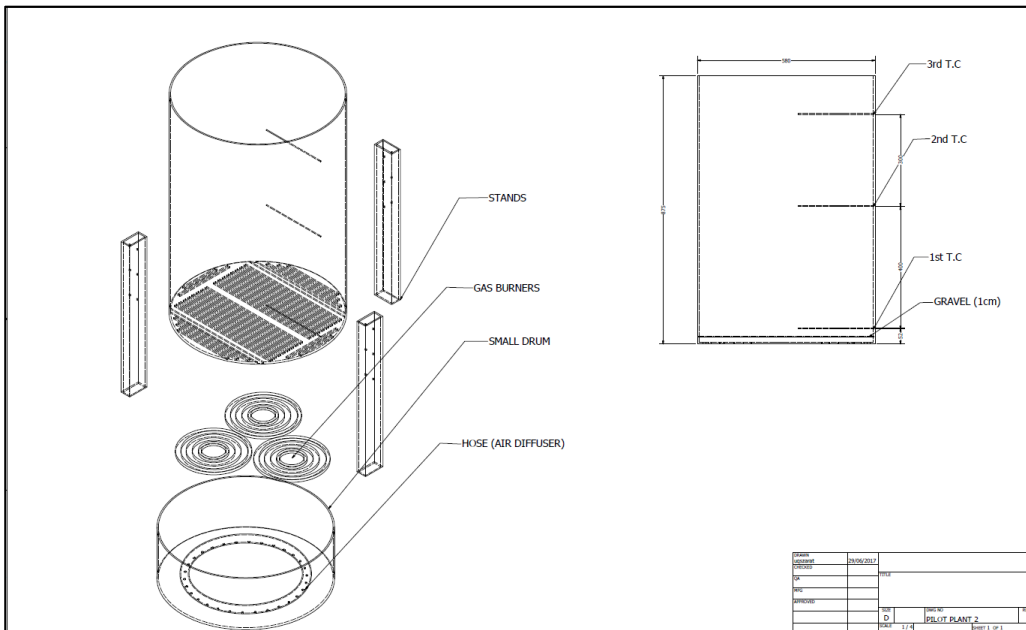
A small and relatively simple smouldering pilot plant has been designed and constructed to facilitate on site testing of the smouldering technology under real world conditions. The pilot is designed to treat 50 kg of paunch per batch run.

### **7.1 Stage 1 Pilot Plant**

#### **7.1.1 Stage 1 Pilot Plant Design**

The pilot plant shown in Figure 14 includes similar elements to the batch laboratory reactor, on a larger scale. Key elements are are:

- Reactor (drum)
- Heating element
- Air supply
- Temperature sensors



**Figure 14: The pilot plant and its components**

#### 7.1.1.1 Reactor

The body of the pilot reactor consisted of a 200 L steel drum, shown in Figure 15. The drum is insulated with a layer of Rockwool<sup>®</sup> (R-value 4.0) material to avoid heat losses. The drum is open in the bottom. A grill and a metallic mesh are placed inside in the bottom of the drum. On top of the mesh, 10 kg of gravel (3-6 mm nominal size from River Sands Pty Ltd) is placed. The gravel has ideal thermal properties and at the same time avoids the direct heating of the waste with fire flames. Therefore, a slow continuous heating is achieved, which is crucial to achieve self-sustaining smouldering. In addition, the layer of gravel avoids the falling ash, during combustion, on top of the air diffuser.

This layer of gravel corresponds to 2 cm. Therefore, TC1 is located at 3 cm from the bottom of the waste bed. The temperature registered in TC1 is used to determine the time of ignition (airflow ON).

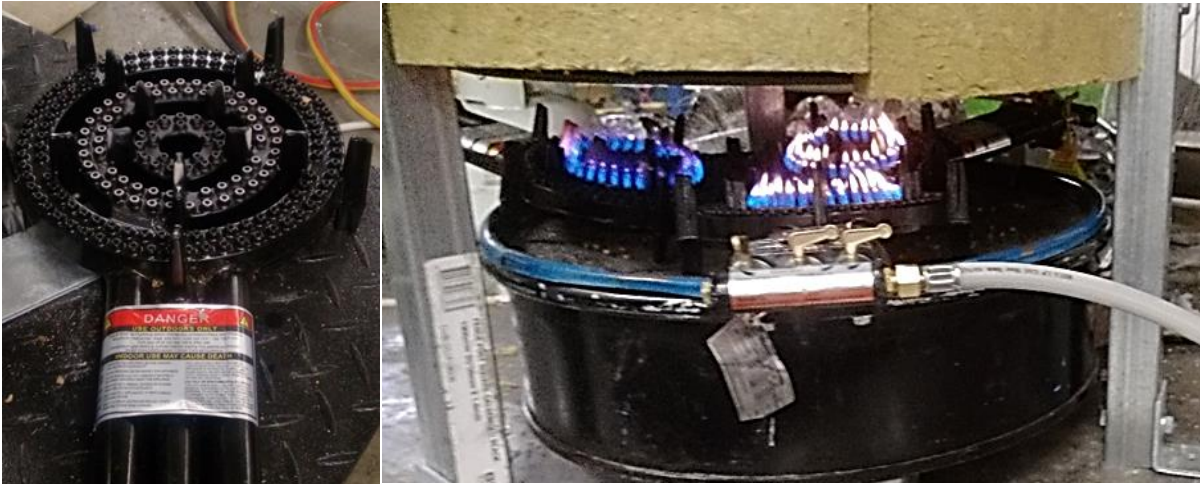




**Figure 15: Steel drum (left), insulation (top right) and internal structure (bottom right)**

#### 7.1.1.2 Heating element

The smouldering requires a heat source during startup to achieve the initial ignition conditions for combustion. In the pilot plant, heat is provided using gas burners. This method of ignition was previously tested at UQ for the smouldering of faeces. The gas burners are placed under the steel drum as shown in Figure 16.



**Figure 16: Gas burners used to provide heat during start-up of the smouldering pilot**

#### 7.1.1.3 Air Supply

The supply of air flow to the smouldering pilot is achieved using a small air compressor. An air diffuser has been installed to ensure a uniform airflow along the whole cross-section of the reactor and complete combustion of the waste.

For the air diffuser, two configurations were tested (see Figure 17): a spiral copper pipe and a hose ring. The hose ring was chosen as it was easier to implement and gave more uniform airflow.



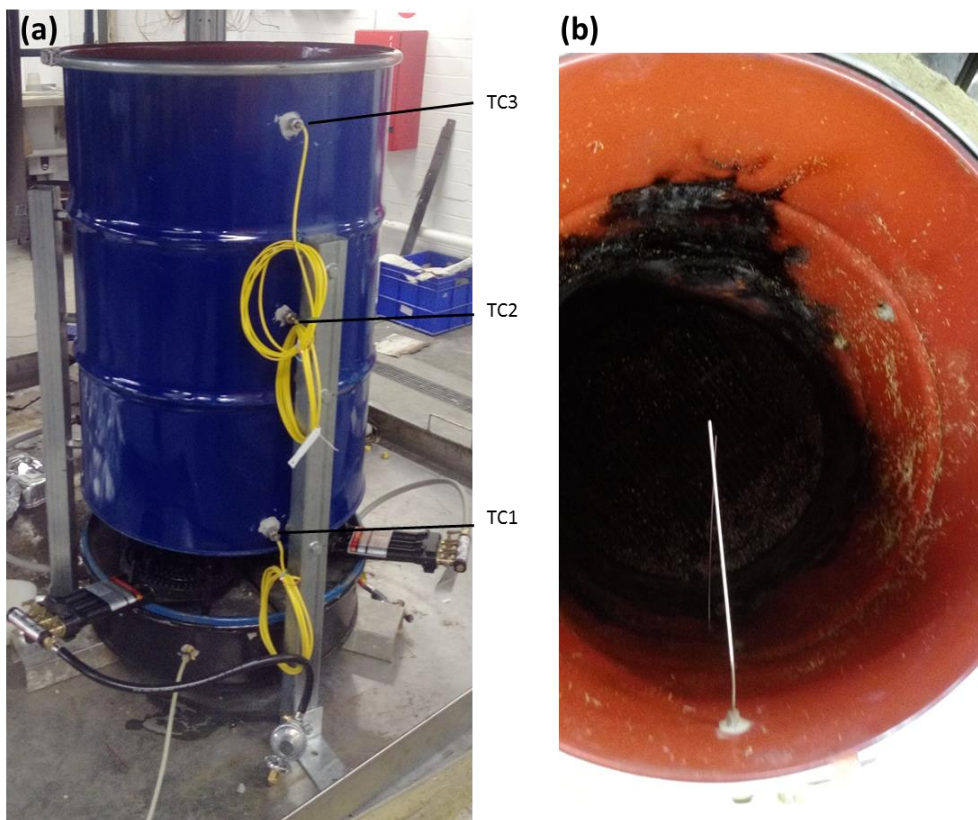
**Figure 17: The two air diffuser configurations tested: (left) spiral copper pipe and (right) hose ring**

#### 7.1.1.4 Temperature sensors

Three K-type thermocouples (TC) were installed in the drum at different heights (Figure 18). The thermocouples are used to measure the temperature of the smouldering bed and track smouldering performance. The relative position and function of each thermocouple is detailed in Table 16.

**Table 16: Position and function of the thermocouples in the reactor**

| Number | Position from bottom of the drum (cm) | Function   |
|--------|---------------------------------------|--|
| TC1    | 3                                     | Allows to determine the ignition (airflow ON)                        |
| TC2    | 43                                    | For the following of the drying/combustion processes                 |
| TC3    | 73                                    | Determines the exit gas/steam temperature, usually above the mixture |



**Figure 18: Thermocouples (TC) in the drum for temperature measurement. (a) outside view, (b) top view.**

## 7.1.2 Stage 1 Pilot Plant Testing

### 7.1.2.1 Waste used in pilot testing

As part of the pilot design and testing, preliminary trials were conducted at UQ using grass clippings collected from the St Lucia Campus. Trials with grass clippings were designed to test the function of the pilot only and are not an indication of the performance expected for paunch. A comparison of the solids content and calorific values for grass clippings and paunch is shown in Table 17. Grass clippings contain a higher ash content and a lower calorific value compared to paunch, and is therefore a more challenging material for self-sustaining smouldering and performance will be conservative.

**Table 17: Comparison of paunch and UQ grass used in initial pilot testing**

|                              | Paunch A | Paunch B | UQ grass |
|------------------------------|----------|----------|----------|
| Moisture (% , wet basis)     | 83       | 77       | 75       |
| Volatiles (% , dry basis)    | 72.2     | 84.6     | 74.3     |
| Fixed carbon (% , dry basis) | 18.5     | 5.9      | 14.2     |
| Ash (% , dry basis)          | 9.4      | 9.5      | 10.0     |
| Energy (kJ/g, dry basis)     | 16.9     | 17.6     | 13.2     |

### 7.1.2.2 Experiments

During each test, the pilot was loaded with a mass of grass clippings, as shown in Table 18. During start-up heat was applied using the gas burners. When the temperature at TC1 reached 250-260 °C, the heating is ceased, and the gas burners are removed and replaced with the air diffuser. Airflow was initiated at 1.7 cm/s (270 L/min).

**Table 18: Mass, initial grass bed height and results of the experiments performed**

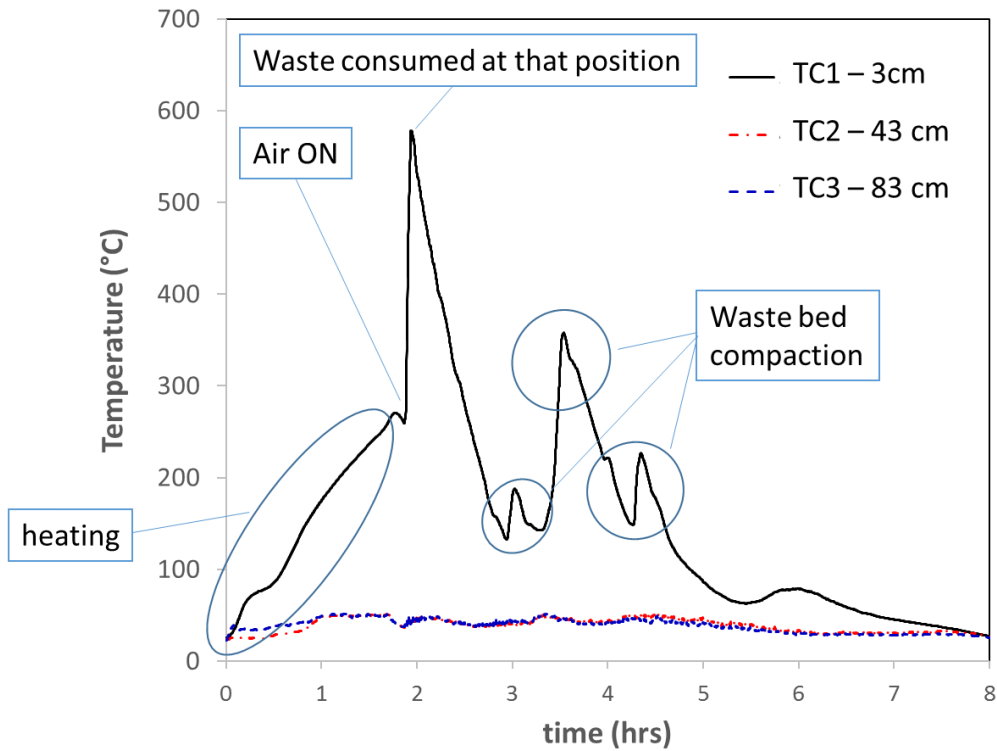
| Experiment | Mass (kg) | Moisture Content (%) | Initial grass bed height (cm) | Self-sustaining? |
|------------|-----------|----------------------|-------------------------------|------------------|
| 1.1        | 20.7      | 70                   | 44                            | YES              |
| 1.2        | 58.7      | 70                   | 84                            | NO               |

The temperature histories for Experiment 1.1 and Experiment 1.2 are shown in Figure 19 and Figure 20 respectively. Experiment 1.1 was successful with self-sustaining smouldering achieved. The start-up period during Experiment 1.1 was approximately 2 hours and heating was applied during this period. Under the start-up conditions, the grass destruction rate was 2.5 kg/h (indicating 20% of the grass was destroyed during start up).

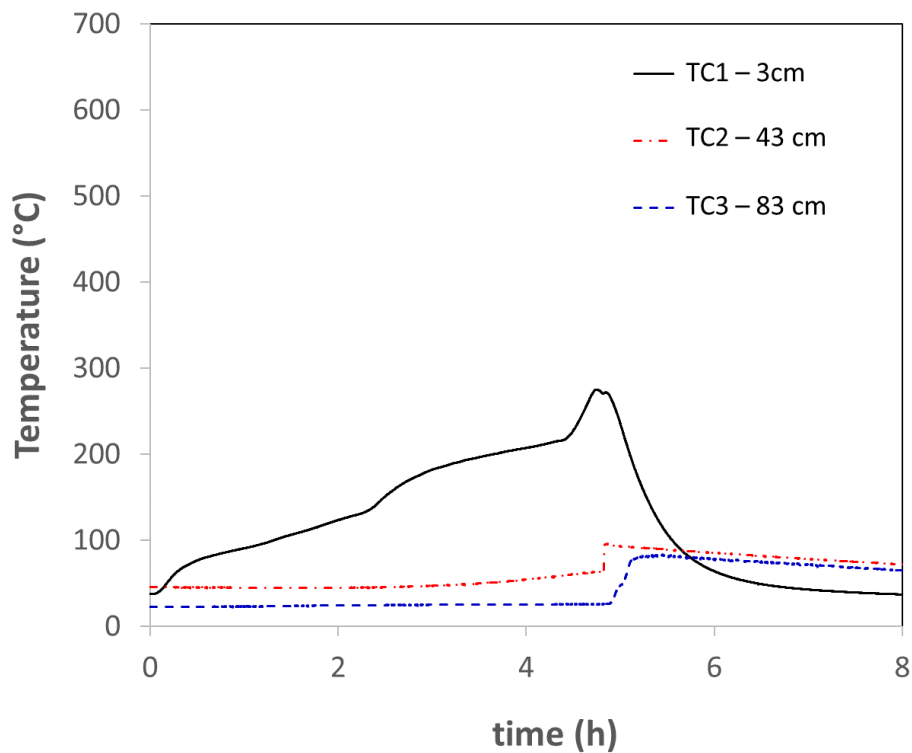
After start-up, heating was removed and air flow initiated. During this period the temperature at the bottom of the reactor rapidly increased as the waste combusted, as the combustible material was

exhausted the temperature decreased (hours 2-3). Sand was not applied to the pilot experiments to maintain the solid bed volume within the reactor, therefore as combustion progressed the bed volume decreased significantly leading to waste bed compaction. The volume reduction and compaction of the waste bed can be seen in Figure 19 as a series of temperature spikes at TC1 between 3-5 hours. These spikes occurred as the bed compacted and the combustion front dropped in height. Overall, the experiment was successful. The highest temperature achieved in the waste bed was 578 °C while the hottest temperature registered in the combustion gases was 52 °C. There were no unburnt grass residues in the drum on completion of the experiment. The final bed height of the ash was 4 cm and 0.67 kg of ash was recovered, this corresponds to a mass reduction of 97%. Considering the large decrease in bed height, it may be possible to operate the equipment as a fed-batch process, where additional material is regularly added to the drum during operation. This may simplify the infrastructure for small applications.

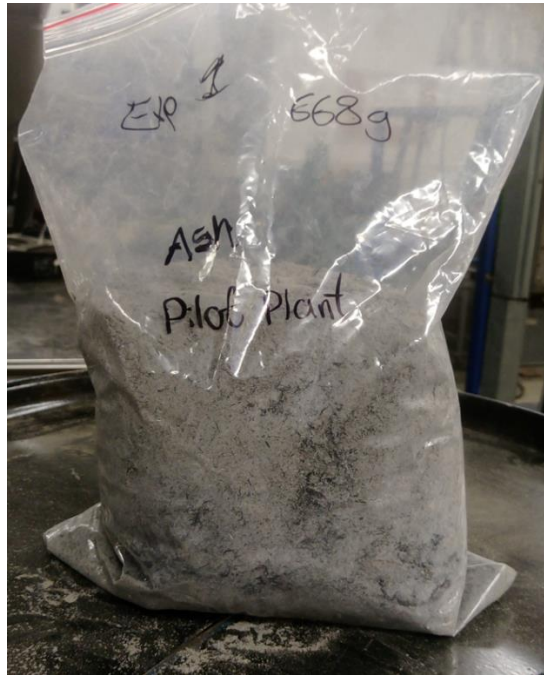
Experiment 1.2 was not successful. Two different causes were identified as likely problems that prevented self-sustaining smouldering. For Experiment 2, the pilot reactor was filled 2 days before ignition. This resulted in increased bed compaction (0.70 kg/cm for EXP2 vs 0.47 kg/cm for Exp 1). The grass clippings contained free moisture. During the 2 day settling period, there was a clear migration of water through the waste bed, evident by water dripping through the bottom of the reactor. The higher moisture and increased bed density at the bottom of the pilot created significantly more challenging conditions for smouldering, resulting in a longer start-up time and unburnt residues after the experiment. This will be addressed through further testing of the pilot, including guidelines around loading and operation.



**Figure 19: Temperature histories in the pilot reactor during Experiment 1.1 (21kg grass clippings at 70% moisture).**



**Figure 20: Temperature histories in the pilot reactor during Experiment 1.2 (59 kg waste at 70% moisture)**



**Figure 21: Ash residues from experiment**

### 7.1.3 Major Challenges – Odor Management

The Stage 1 pilot plant was moderately successful, however experiments identified that bed height and bed compaction were issues that needed to be managed during operation. Bed management is only an issue when a porous medium such as sand is not used during smouldering.

The Stage 1 pilot was an open reactor design, initially developed to be combined with a fumehood for collection and management of combustion off gas. However, when moved to site without a fumehood odour management became a major issue. Odour management was identified as a major barrier against progressing smouldering technology in the red meat industry.

## 7.2 Stage 2 Pilot Plant

### 7.2.1 Stage 2 Pilot Plant Design

The Stage 2 Smouldering Pilot Plant incorporated an enclosed reactor design, combined with an off-gas condenser and activated carbon filter for odour management. The upgraded Stage 2 pilot plant schematic is shown in Figure 22, images of the Stage 2 pilot and components are shown in Figure 23. The main design components included:

- Reactor: 200-litres steel drum wrapped in fibre glass insulation (R-value=4.0).
- Heating element: 5 electric coil heaters of 500W each.

- Air supply: air blower connected to an air diffuser through a hose.
- Air flowmeter and pressure sensor located at the air inlet hose.
- Temperature sensors: 15 thermocouples (K-type) placed at different heights inside the reactor. The thermocouples are connected to a Data Logger and PC to record temperature as a function of time.
- Gas treatment system: hood placed atop reactor connected to condenser. Condenser is composed by a stainless steel coil submerged into cool water. Liquids are collected in a 60L drum. The gases are treated using activated carbon filters.



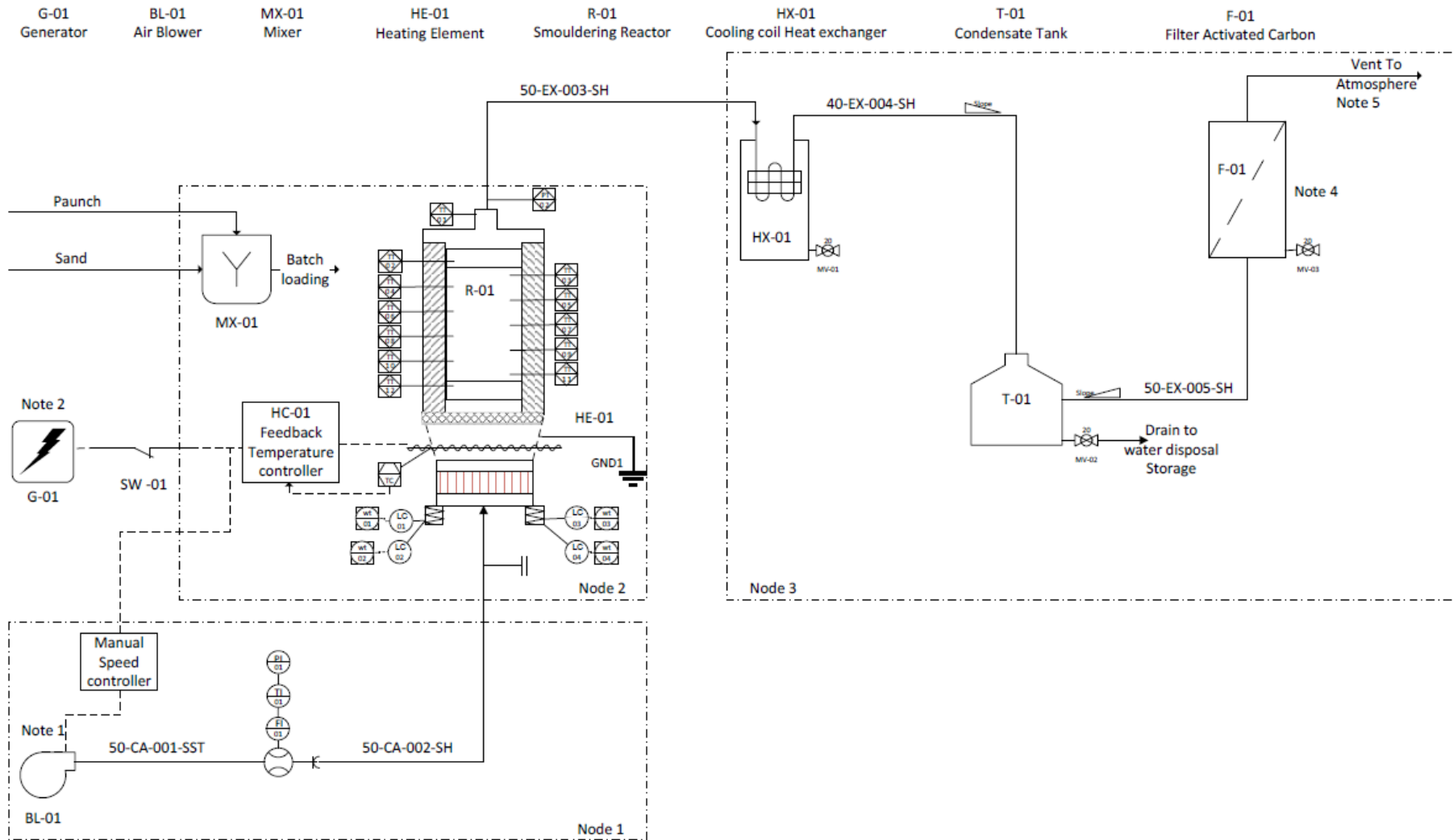


Figure 22: Schematic showing the design of the upgraded Stage 2 pilot plant and its components (Note: Equipment not AMPC funded).

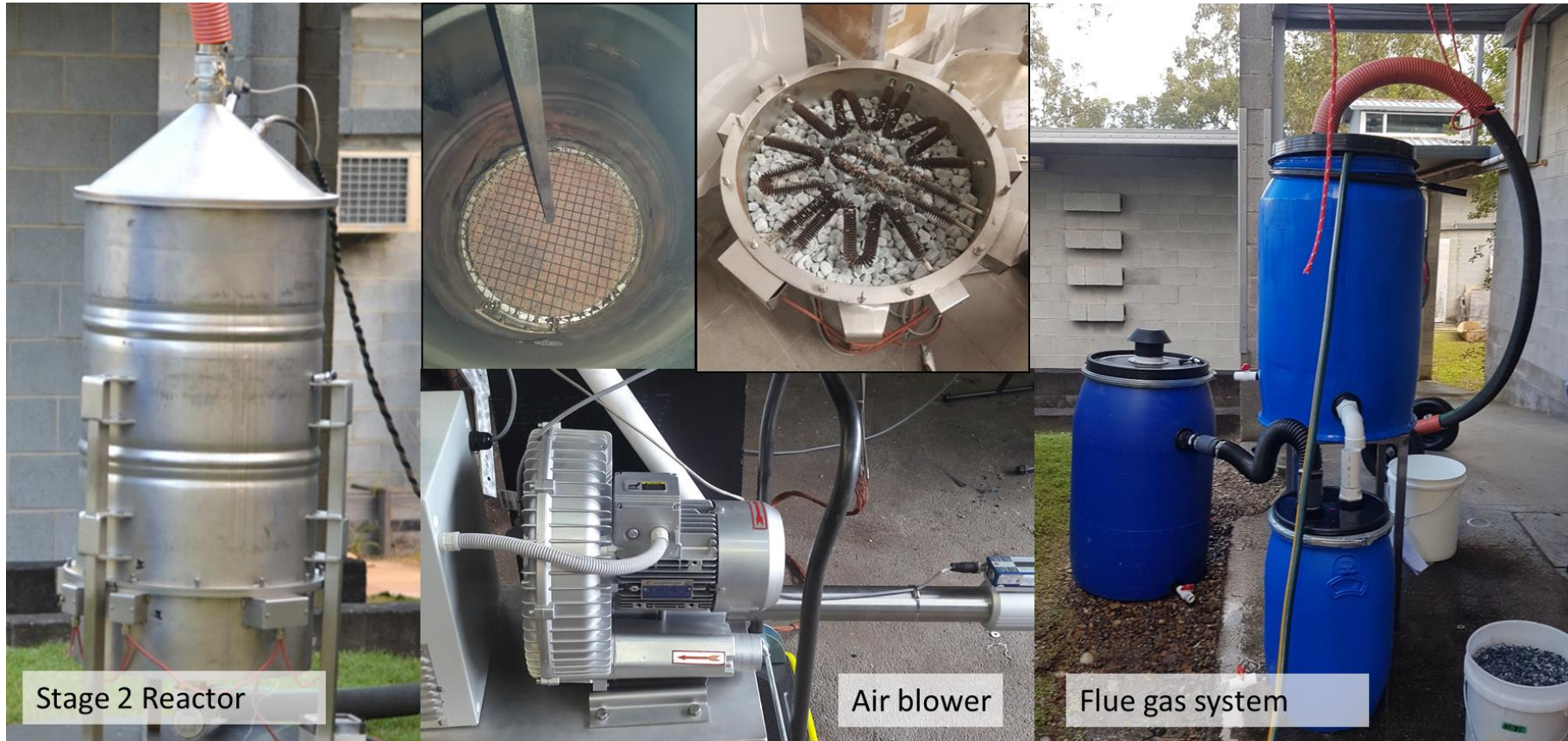


Figure 23: Images showing the design of the upgraded Stage 2 pilot plant and its components. (Note: Equipment not AMPC funded).

### 7.2.1.1 Reactor

The second-generation smouldering pilot reactor is a 200L carbon steel drum. Stainless steel is the recommended material for a full-scale process, due to enhanced corrosion protection. The differences between carbon steel and stainless steel will not produce differences in the experiment's outcomes. The drum is insulated with a layer of fibre glass (Rockwool®, R-value 4.0) material to avoid heat losses and protect the equipment operators from the heat.

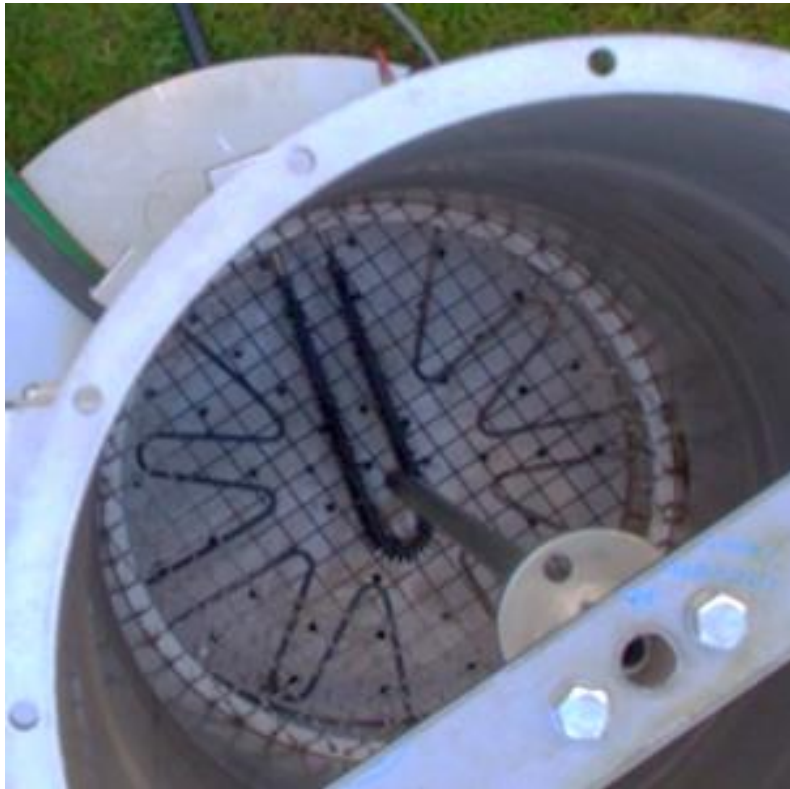
### 7.2.1.2 Heating element

Reactor pre-heating is achieved using five 500W electric heaters installed into the reactor base (Figure 24). Electric heaters replace the gas heaters used on the first generation pilot. Electric heaters were used previously in laboratory scale experiments, and resulted more effective heating compared to the gas burners. Electric heaters require electrical power, but do not require gas installation, allowing for faster and simpler pilot installation.

As previously described, the heaters are used to increase the temperature at the bottom of the waste bed, to a certain temperature (usually between 250 and 450 °C). Once this temperature is reached (measured with a thermocouple placed at 2 cm from the heating element, the airflow is initiated and the heating is ceased.

### 7.2.1.3 Air Supply

Airflow is provided by an air blower connected to an air flow meter, shown previously in Figure 23. The air enters the smouldering reactor through an air diffuser shown in Figure 24. The air diffuser ensures uniform airflow along the whole cross-section of the reactor. Uniform airflow is critical to manage the combustion front and enable successful smouldering.



**Figure 24: Electric heater elements placed at the bottom of the steel drum base. The air diffuser can be seen below the heating elements. Above the heating elements, there is a grill to avoid contact of the material with them. A layer of gravel is placed atop the grill. The waste bed lays over the gravel layer.**

#### 7.2.1.4 Temperature sensors

The temperature profile in the smouldering pilot is measured using fourteen K-type thermocouples (TC) placed vertically at different heights inside a thermowell within the reactor. The thermowell is located at the centre of the drum (see Figure 5). The thermocouples are connected to a Data Logger and to a computer to record the temperatures every 20 seconds. The concentration of TCs towards the bottom of the reactor is to increase the resolution in the combustion zone as the bed waste compacts as this is consumed. This allows to determine the performance of the experiment online. The relative position of each one from the bottom of the reactor are detailed in Table 1.

**Table 19: Position of the thermocouples in the reactor relative to the bottom of the drum.**

| Name          | TC1 | TC2 | TC3 | TC4 | TC5 | TC6 | TC7 | TC8 | TC9 | TC 10 | TC 11 | TC 12 | TC 13 | TC 14 |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|-------|-------|-------|-------|
| Position (cm) | 1   | 2   | 3   | 4   | 5   | 10  | 15  | 20  | 25  | 30    | 40    | 50    | 60    | 70    |



**Figure 25: Thermocouples through the lid of the drum (left) and thermowell (right) used to place the thermocouples vertically, inside, and in the centre of the reactor.**

#### 7.2.1.5 Flue Gas Collection system

The flue-gas collection system is a critical feature of the upgraded pilot plant, designed to capture and manage odor during smouldering. The collection system included following elements:

- Reactor hood
- Condenser
- Drum for collection of condensables (liquids)
- Activated carbon filter

During operation, steam, moist air and volatile liquids (i.e. oils) from the smouldering process are collected by the reactor hood and passed through a condenser unit. The condenser unit is a steel coil submerged in a 200L drum of water (water may be chilled to aid condensation). The condensable liquid is then collected in a second 200L drum before the remaining air/exhaust gases are passed a gas cleaning unit. Flue gas is not actively extracted from the reactor headspace and requires airflow from the blower at the base of the reactor to push air from the headspace, as a result, there is no flow through the gas collection system during initial reactor heat up.

## **7.2.2 Stage 2 Pilot Plant Testing**

### 7.2.2.1 Waste used in pilot testing

Paunch solid waste used in Stage 2 pilot testing was again collected from Site A. Characteristics are shown in Table 20.

**Table 20: Dewatered Paunch used in Stage 2 Pilot Testing**

|                              | Paunch A<br>2018 |
|------------------------------|------------------|
| Moisture (% , wet basis)     | 83               |
| Volatiles (% , dry basis)    | 72.2             |
| Fixed carbon (% , dry basis) | 18.5             |
| Ash (% , dry basis)          | 9.4              |
| Energy (kJ/g, dry basis)     | 16.9             |

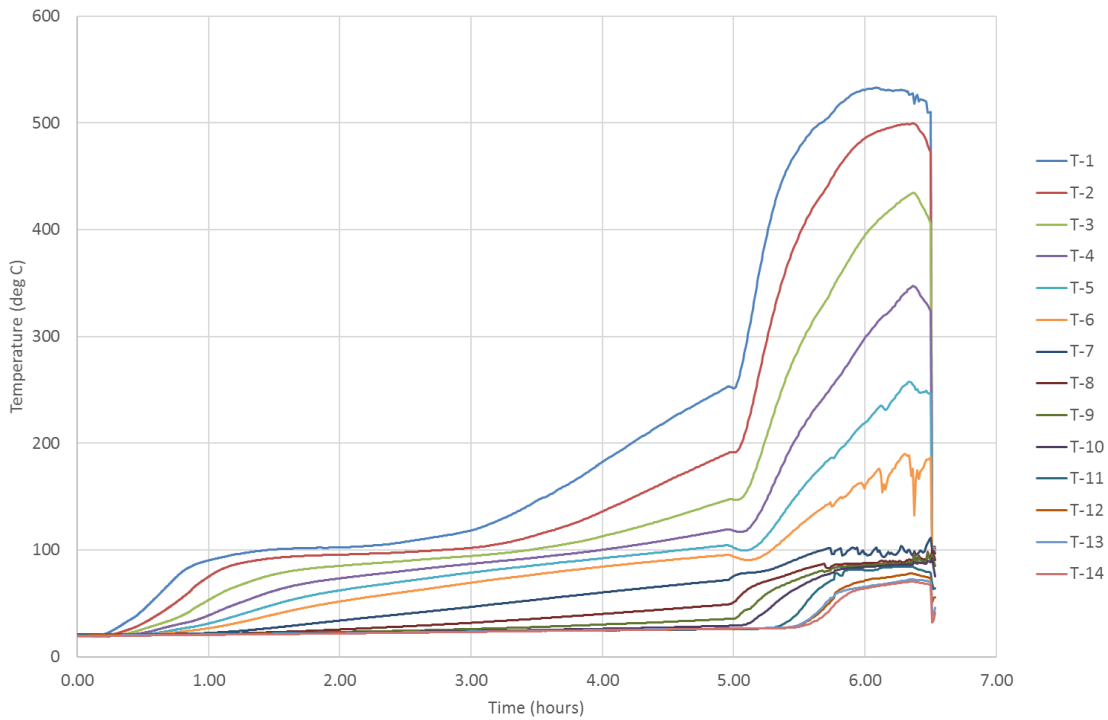
#### 7.2.2.2 *Experiments*

During each test, the pilot was loaded with a mixture of paunch solid waste and sand as described in Table 21. Paunch was pre-dried to a moisture content of approximately 70% prior to the experiments. Sand was used in the experiments to provide a larger volume of inert material and therefore reduce bed collapse during the smouldering process.

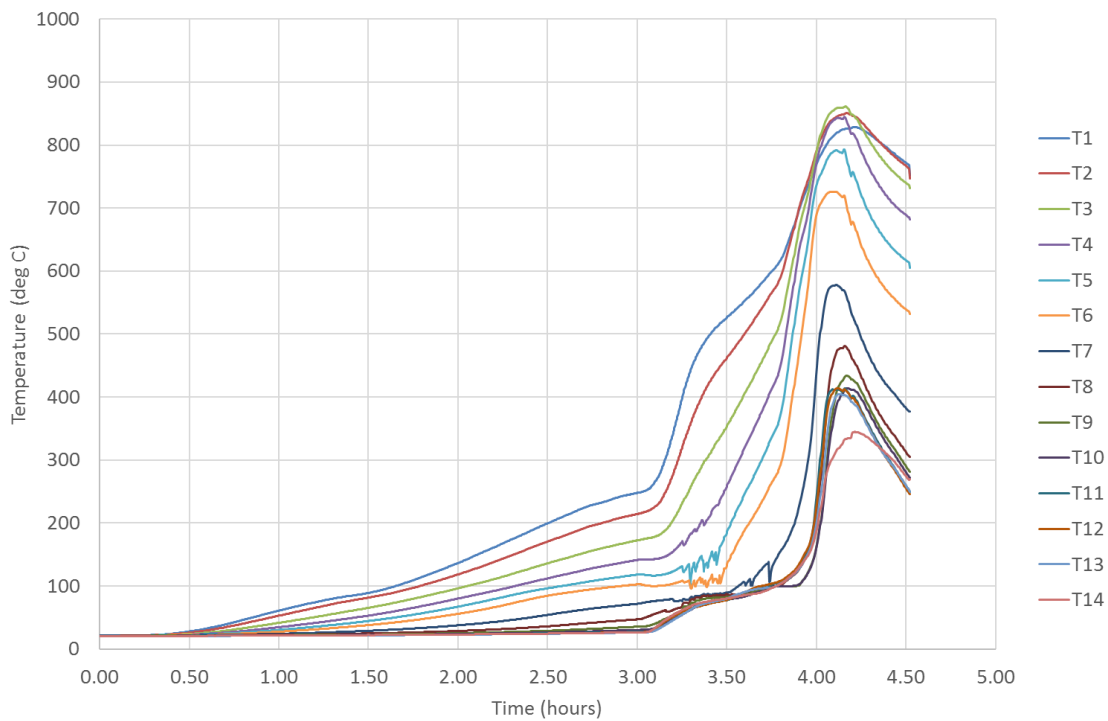
**Table 21: Mass, initial grass bed height and results of the experiments performed**

| Experiment | Mass (kg) | Moisture Content (%) | Sand (kg) | Initial grass bed height (cm) |
|------------|-----------|----------------------|-----------|-------------------------------|
| 2.1        | 10        | 70                   | 20        | 52                            |
| 2.2        | 10        | 70                   |           | 52                            |

The temperature histories for Experiment 2.1 and Experiment 2.2 are shown in Figure 26 and Figure 27 respectively. Neither experiment was completed successfully, partly due to some equipment issues and the presence of excess odor. The activated carbon filters did not completely remove odor and this was seen as a major barrier to completing experiments and progressing onsite technology development.



**Figure 26: Temperature histories in the Stage 2 pilot reactor during Experiment 2.1 (10 kg waste at 70% moisture and 20kg sand)**



**Figure 27: Temperature histories in the Stage 2 pilot reactor during Experiment 2.2 (10 kg waste at 70% moisture and 20kg sand)**

### 7.2.3 Major Challenges

#### Water Condensation and Quenching

Large-scale batch experiments using the Stage 2 pilot plant were not successful. During testing, the pilot was loaded with a mixture of paunch and sand. During start-up heat was applied using the electric heating elements, during this initial heating phase, there was significant evaporation from the waste bed. There was no airflow during this period and the evaporated water re-condensed on the reactor hood. The condensed water dripped back onto the surface of the waste bed, significantly increasing the moisture content of this zone, as a result of the high moisture content in the upper region of the bed, the smouldering experiments had problems with quenching and complete self-sustaining smouldering was not achieved.

The evaporation and condensation of water during start up may be addressed through further development of the reactor design, such as the inclusion of an extraction fan in the reactor headspace to operate during the initial heating phase.

#### Odor Management

Odor management remains a major hurdle for onsite application of smouldering technology at RMP. The Stage 2 pilot plant trialed a series of activated carbon filters, these filters reduced odor, however odour was not eliminated and was identified by the project team as a major operation risk that needed to be resolved before further development and testing of smouldering technology.

### 7.3 Further Development Required

Odor management is the most significant barrier to progressing smouldering technology onsite at red meat processing plants. The flue gas and odor management system needs to be robust, comprehensive and able to treat and deal with different solid wastes containing different organic components, different metals contaminants/pollutants and different moisture contents.

Development and testing of odor management technology is beyond the scope of this project, and detailed analysis of flue gas composition and quality has not been completed. However, Table 22 provides an overview of pollutants and concentrations that may be expected within the flue gas. The values provided below are conservative numbers and are not based on detailed experimental work from the current project.



**Table 22: Pollutants, expected levels in the flue gas and required effluent quality (Environmental Protection Air Policy 2009, Queensland Government)**

| <i>Pollutant</i>                  | <b>Maximum expected pollutant levels</b> | <b>Required effluent quality flue gas</b> | <b>Units</b>             |
|-----------------------------------|--|---|--------------------------|
| PM (less than 10 microns)         | 11,000                                   | 50 (24h)                                  | µg/m <sup>3</sup>        |
| PM (less than 2.5 microns)        | 50,000                                   | 25 (24h)<br>8 (1y)                        | µg/m <sup>3</sup>        |
| Total Hydrocarbons <sup>l</sup>   | 1.8                                      | 0.3 (1y)                                  | ng/sm <sup>3</sup> (Dry) |
| NO <sub>x</sub> <sup>b)</sup>     | No accurate data available               | 250 (1h)<br>33 (1y)                       | mg/m <sup>3</sup>        |
| SO <sub>x</sub> <sup>b)</sup>     | No accurate data available               | 570 (1h)<br>230 (24h)<br>57 (1y)          | µg/m <sup>3</sup>        |
| CO <sup>d)</sup>                  | Up to 5% (62.5g/m <sup>3</sup> )         | 11 (8h)                                   | mg/m <sup>3</sup>        |
| VOCs <sup>a)</sup>                | See appendix                             | NA  |                          |
| Dioxins and furans <sup>a)</sup>  | 0.577 ng/m <sup>3</sup>                  | 125                                       | ng/sm <sup>3</sup> (Dry) |
| Dioxin-like PCBs                  | 0.033 ng/m <sup>3</sup>                  |   |                          |
| Acids <sup>c)</sup>               | 25                                       | NA  | mg/m <sup>3</sup>        |
| Aldehydes <sup>c)</sup>           | 15                                       | NA  | mg/m <sup>3</sup>        |
| Benzene <sup>a)</sup>             | See appendix                             | 10 (1y)                                   | µg/m <sup>3</sup>        |
| Toluene <sup>a)</sup>             | See appendix                             | 4.1 (24h)<br>410 (1y)                     | mg/m <sup>3</sup>        |
| Xylenes <sup>a)</sup>             | See appendix                             | 1.2 (24h)<br>0.95 (1y)                    | mg/m <sup>3</sup>        |
| Tetrachloroethylene <sup>a)</sup> | See appendix                             | 0.27 (1y)<br>8.6 (30min)                  | mg/m <sup>3</sup>        |
| Styrene <sup>a)</sup>             | See appendix                             | 280 (1w)<br>75 (30min)                    | µg/m <sup>3</sup>        |

a) Emissions data obtained during batch testing of sludge smouldering at the University of Ontario (data provided by Geosyntec)

b) There is no accurate data available on the NO<sub>x</sub> and SO<sub>x</sub> emission during smouldering combustion of paunch/sludge. For the design criteria, it should be assumed that the formation potential of these compounds is equal to conventional incineration of sludge.

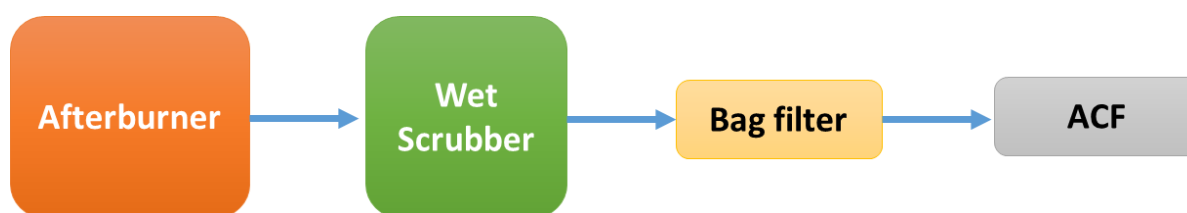
c) Emissions of other species are estimated based on a review document (Int J. Wildland Fire (2018), 27, 293-312), considering the highest concentrations.

d) The CO levels are estimated from laboratory data.

Detailed assessments of the flue gas emissions from smouldering combustion are required to design an appropriate and robust odor management process. However, Table 23 provides a summary of key pollutants and typical treatment strategies, preferred treatment options are highlighted in bold. A potential flue gas treatment process combining the selected treatment steps is summarized in Figure 28.

**Table 23: Summary of Pollutants during smouldering combustion and typical treatment technologies**

| Pollutant             | Potential mitigation, levels and comments  | Anticipated treatment                                     |
|-----------------------|--|---|
| 1. PM                 | Not expected, or minor quantities  | Cyclones<br><b>Bag filters</b>                            |
| 2. Heavy Metals       | Associated with PM. Reduced if WWTP sludge with minimal amount of heavy metals   | Cyclones<br><b>Bag filters</b><br>ESP for Hg              |
| 3. CO                 | Some control with operation parameters, mainly airflow rate  | <b>Afterburner</b>  |
| 4. VOCs               | Some control adjusting smouldering temperature   | <b>AC Filter</b><br><b>Afterburner</b>                    |
| 5. NOx                | Reduced formation due to low temperatures. Reduced if WWTP sludge with minimal N concentration. High air excess during smouldering for reduced emissions | <b>Wet scrubber</b><br>Reducing agents                    |
| 6. SO <sub>2</sub>    | Reduced if WWTP sludge with minimal S concentration  | <b>Wet scrubbers</b>                                      |
| 7. Dioxins and furans | Expected only those present originally in sludge as temperatures in flue gas are not enough for PCDD/Fs formation  | <b>AC Filter</b>  |
| 8. Odours             | Expected. Concentrations are a function of the amount of waste treated.  | <b>AC Filter</b><br><b>Afterburner</b><br><b>Scrubber</b> |



**Figure 28: Schematic representation of the gas emission control system for the flue gas from smouldering combustion of WWTP sludge**

The proposed gas treatment train contains an afterburner placed straight after the smouldering reactor to remove the CO, VOCs and odours. The afterburner also has the potential to decompose PDDC/Fs, if these are present in the waste. In addition, there is no necessity of pre-treatment or cooling down the temperature of the flue gas as the afterburner occurs at high temperatures.

A wet scrubber is proposed to reduce the temperature of the gases and capture NO<sub>x</sub> and SO<sub>2</sub>. Due to

the mechanism of the scrubber, which acts as a “shower” for the gases, some particulate matter and heavy metals can be also retained in the precipitate, while some odours can be dissolved in the liquid.

After the scrubber, a bag filter can be used to retain any solid particles (PM) that remain in the flue gas. Only very fine PM may be present at this stage, and in low quantities, and therefore a simple and non-expensive bag filter will suffice. Finally, if any VOCs, PCCD/Fs or odours are present after the afterburner, these will be removed in the activated carbon filter placed at the very end of the gas treatment system.

In addition to the gas treatment system proposed here, process operating conditions can also be tuned to manage flue gas composition. For example, the levels CO and VOCs can be minimized using excess airflow. However, this increased airflow can lead to increased combustion temperatures, leading to more NO<sub>x</sub> and SO<sub>2</sub> formation. Some temperature control can be achieved by manipulating the sand-waste ratio and by pre-drying or changing the upstream dewatering operations. Lower smouldering temperatures can reduce the production of “thermal NO<sub>x</sub>”. However, as paunch contains a significant nitrogen concentration, some levels of “fuel NO<sub>x</sub>” are expected. The levels of SO<sub>2</sub> will depend on the sulphur content in the waste, so SO<sub>2</sub> may be expected in the flue gas.

## **8 PRELIMINARY COST BENEFIT ANALYSIS**

Preliminary cost-benefit analysis for smouldering is based on a technology leasing model. The operating costs for processing paunch waste are \$8-18/wet ton and include the costs of leasing the smouldering equipment. This cost data was provided by Geosyntec. Analysis was conducted considering average paunch disposal costs of \$10/wet ton, \$20/wet ton \$50/wet ton. The analysis shows that the benefits of smouldering are highly dependant on current paunch disposal costs. At the current cost of \$10/ton, smouldering is cost neutral or negative. However, for paunch disposal costs at \$50/ton, the cost benefit of smouldering exceeds \$300,000 per year for a plant processing 1,500 head per day (250 processing days per year). Savings are largely due to removal of the high moisture content and the high organic fraction during the smouldering process and extremely effective volume reduction. Operating costs do not include the gas treatment processes, which may substantially change the result.

**Table 24: Cost-benefit analysis based on preliminary results for a slaughterhouse processing 1,500 head per day (cost of paunch disposal \$10/wet ton, paunch production of 7kg dry/head).**

| Parameter                        |               | Conventional paunch management            | Smouldering approach  |
|----------------------------------|---------------|---|-----------------------|
| <b>Waste Production</b>          |               |   |                       |
| Daily paunch production          | (ton ds/day)  | 10  | 10                    |
| Dry solids content               | (wt%)         | 25  | 25                    |
| Organic content dewatered paunch | (% TS)        | 85  | 85                    |
| Daily paunch production          | (wet ton/day) | 40  | 40                    |
| <b>Treatment Costs</b>           |               |   |                       |
| OPEX smouldering reactor         | (\$/dry ton)  | n.a.                                      | \$35-70 <sup>a)</sup> |
| OPEX smouldering reactor         | (\$/wet ton)  | n.a.                                      | \$8-18 <sup>a)</sup>  |
| OPEX smouldering reactor         | (\$/year)     | n.a.                                      | \$87,500-\$175,000    |
| <b>Final Disposal Costs</b>      |               |   |                       |
| Solid Waste for disposal         | (wet ton/day) | 40  | 1.5                   |
| Paunch disposal costs            | (\$/wet ton)  | \$10                                      | \$10                  |
| Paunch disposal costs            | (\$/year)     | \$100,000                                 | \$3,750               |
| <b>Net benefit (\$/year)</b>     |               | <b>-\$80,000 to \$10,000<sup>b)</sup></b> |                       |

a) OPEX is based on data full-scale smouldering reactor for remediation of tar-contaminated soil. This is a conservative cost estimate and includes leasing of smouldering equipment, with further cost reductions expected to be achievable.

b) Additional economic benefits arising from targeted nutrient recovery not taken into account.

**Table 25: Cost-benefit analysis based on preliminary results for a slaughterhouse processing 1,500 head per day (cost of paunch disposal \$20/wet ton, paunch production of 7kg dry/head).**

| Parameter                        |               | Conventional paunch management         | Smouldering approach  |
|----------------------------------|---------------|--|-----------------------|
| <b>Waste Production</b>          |               |  |                       |
| Daily paunch production          | (ton ds/day)  | 10                                     | 10                    |
| Dry solids content               | (wt%)         | 25                                     | 25                    |
| Organic content dewatered paunch | (% TS)        | 85                                     | 85                    |
| Daily paunch production          | (wet ton/day) | 40                                     | 40                    |
| <b>Treatment Costs</b>           |               |  |                       |
| OPEX smouldering reactor         | (\$/dry ton)  | n.a.                                   | \$35-70 <sup>a)</sup> |
| OPEX smouldering reactor         | (\$/wet ton)  | n.a.                                   | \$8-18 <sup>a)</sup>  |
| OPEX smouldering reactor         | (\$/year)     | n.a.                                   | \$87,500-\$175,000    |
| <b>Final Disposal Costs</b>      |               |  |                       |
| Solid Waste for disposal         | (wet ton/day) | 40                                     | 1.5                   |
| Paunch disposal costs            | (\$/wet ton)  | \$20                                   | \$20                  |
| Paunch disposal costs            | (\$/year)     | \$200,000                              | \$7,500               |
| <b>Net benefit (\$/year)</b>     |               | <b>\$20,000-\$100,000<sup>b)</sup></b> |                       |

a) OPEX is based on data full-scale smouldering reactor for remediation of tar-contaminated soil. This is a conservative cost estimate and includes leasing of smouldering equipment, with further cost reductions expected to be achievable.

b) Additional economic benefits arising from targeted nutrient recovery not taken into account.

**Table 26: Cost-benefit analysis based on preliminary results for a slaughterhouse processing 1,500 head per day (cost of paunch disposal \$50/wet ton, paunch production of 7kg dry/head).**

| Parameter                        |               | Conventional paunch management        | Smouldering approach  |
|----------------------------------|---------------|---------------------------------------|-----------------------|
| <b>Waste Production</b>          |               |                                       |                       |
| Daily paunch production          | (ton ds/day)  | 10                                    | 10                    |
| Dry solids content               | (wt%)         | 25                                    | 25                    |
| Organic content dewatered paunch | (% TS)        | 85                                    | 85                    |
| Daily paunch production          | (wet ton/day) | 40                                    | 40                    |
| <b>Treatment Costs</b>           |               |                                       |                       |
| OPEX smouldering reactor         | (\$/dry ton)  | n.a.                                  | \$35-70 <sup>a)</sup> |
| OPEX smouldering reactor         | (\$/wet ton)  | n.a.                                  | \$8-18 <sup>a)</sup>  |
| OPEX smouldering reactor         | (\$/year)     | n.a.                                  | \$87,500-\$175,000    |
| <b>Final Disposal Costs</b>      |               |                                       |                       |
| Solid Waste for disposal         | (wet ton/day) | 40                                    | 1.5                   |
| Paunch disposal costs            | (\$/wet ton)  | \$50                                  | \$50                  |
| Paunch disposal costs            | (\$/year)     | \$500,000                             | \$18,750              |
| <b>Net benefit (\$/year)</b>     |               | <b>\$300,000-400,000<sup>b)</sup></b> |                       |

<sup>a)</sup> OPEX is based on data full-scale smouldering reactor for remediation of tar-contaminated soil. This is a conservative cost estimate and includes leasing of smouldering equipment, with further cost reductions expected to be achievable.

<sup>b)</sup> Additional economic benefits arising from targeted nutrient recovery not taken into account.

## 9 CONCLUSIONS/ RECOMMENDATIONS

Smouldering combustion has emerged as an alternative treatment option for organic solid wastes with high moisture contents (80-85% wt), with some success in similar applications from other industries. Technology reviews suggest that smouldering is suitable for application for all solid organic wastes produced at RMP. Smouldering may be applied as a stand-alone technology with the capacity to reduce 1 ton of dewatered meat processing solid organic waste (moisture content 75-80% wt and organic solids at 90% of dry matter) to approximately 20-30 kg of ash, without the need for external fuel or heat input. Importantly, smouldering can be applied to these wastes directly, or after application of energy recovery technologies such as Anaerobic Digestion. The use of anaerobic digestion as a smouldering pre-treatment will not impact the final solids for disposal, however AD may improve paunch dewatering and facilitate energy recovery in the order of 8GJ/dry ton paunch.

Proof-of-concept testing has been conducted at laboratory scale, with the following outcomes:

- Self-sustaining smouldering of paunch can be achieved without the addition of a porous sand medium, this may reduce the complexity of plant design and operation (i.e. no required to mix paunch and sand before smouldering and no requirement to separate ash and sand after smouldering).
- Results showed that the limits for moisture content and air flowrate are 75% and 1 cm/s, respectively. This result demonstrates that smouldering could be applied to many RMP using paunch processing with currently used dewatering technologies, no addition pre-drying is required. Small scale laboratory experiments are less efficient than large scale reactors, therefore these results are expected to be conservative and further

improvements are expected.

- The maximum smouldering temperature increases when the moisture content is decreased, reaching over 1000°C at 65% moisture. However, the destruction rate decreases. Higher temperatures may increase the risk of NOx in the flue gas.
- The maximum smouldering temperature increases in a near linear relationship when air flowrate increases. However, the impact on the temperature can be neglected.

Scale-up and batch field experiments conducted during the project were less successful. Early pilot experiments were completed successfully and demonstrated self-sustaining smouldering could be achieved, however odor was identified as a critical issue during these initial tests and the pilot was redesigned prior to further field-testing. Experiments in an upgraded pilot plant, with a hooded design to capture flue-gas for odor management, were not successful. The hooded reactor design can result in re-condensation of evaporated water within the reactor, and subsequent quenching of the smouldering combustion. This re-condensation occurs during the initial heat up period and would not be a major issue once a continuous processes was established, however this remains a design flaw to be addressed.

The hooded reactor used a condenser to capture water, steam and condensable liquids produced during the smouldering process, combined with an activated carbon filter to reduce odor. The activated carbon filter was not successful and odor management remains a significant barrier to progressing smouldering technology onsite at red meat processing plants.

## 10 BIBLIOGRAPHY

Appels, L., Baeyens, J., Degrève, J. and Dewil, R. (2008) Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy and Combustion Science* 34(6), 755-781.

Baroutian, S., Smit, A.-M., Andrews, J., Young, B. and Gapes, D. (2015) Hydrothermal degradation of organic matter in municipal sludge using non-catalytic wet oxidation. *Chemical Engineering Journal* 260, 846-854.

Bertanza, G., Galessi, R., Menoni, L., Salvetti, R., Slavik, E. and Zanaboni, S. (2015) Wet oxidation of sewage sludge: full-scale experience and process modeling. *Environmental Science and Pollution Research* 22(10), 7306-7316.

Donatello, S. and Cheeseman, C.R. (2013) Recycling and recovery routes for incinerated sewage sludge ash (ISSA): A review. *Waste Manag* 33(11), 2328-2340.

Fonts, I., Gea, G., Azuara, M., Ábrego, J. and Arauzo, J. (2012) Sewage sludge pyrolysis for liquid production: A review. *Renewable and Sustainable Energy Reviews* 16(5), 2781-2805.

Fytily, D. and Zabaniotou, A. (2008) Utilization of sewage sludge in EU application of old and new methods—A review. *Renewable and Sustainable Energy Reviews* 12(1), 116-140.

Husillos Rodríguez, N., Martínez-Ramírez, S., Blanco-Varela, M.T., Donatello, S., Guillem, M., Puig, J., Fos, C., Larrotcha, E. and Flores, J. (2013) The effect of using thermally dried sewage sludge as an alternative fuel on Portland cement clinker production. *Journal of Cleaner Production* 52, 94-102.

Li, H., Jiang, L.-B., Li, C.-Z., Liang, J., Yuan, X.-Z., Xiao, Z.-H., Xiao, Z.-H. and Wang, H. (2015) Co-pelletization of sewage sludge and biomass: The energy input and properties of pellets. *Fuel Processing Technology* 132, 55-61.

MLA/AMPC (2012) Project Number A.ENV.131 Energy and Nutrient analysis on Individual Waste Streams.

MLA/AMPC (2013) Project Number A.ENV.151 NGRS and Wastewater Management – mapping waste streams and quantifying the impacts.

MLA/AMPC. (2013) Project A.ENV.0153 Paunch Value Adding: Energy, Nutrient Recovery and Reducing Carbon Exposure. .

Rashwan, T.L., Gerhard, J.I. and Grant, G.P. (2016) Application of self-sustaining smouldering combustion for the destruction of wastewater biosolids. *Waste Management* 50, 201-212.

Wei, Y.-S., Fan, Y.-B. and Wang, M.-J. (2001) A cost analysis of sewage sludge composting for small and mid-scale municipal wastewater treatment plants. *Resources, Conservation and Recycling* 33(3), 203-216.

Adam, T., Streibel, T., Mitschke, S., Mühlberger, F., Baker, R. R. and Zimmermann, R. “Application of time-of-flight mass spectrometry with laser-based photoionization methods for analytical pyrolysis of PVC and tobacco,” *J. Anal. Appl. Pyrolysis*, vol. 74, no. 1–2, pp. 454–464, 2005.

Aldushin, A.P., Rumanov, I.E. and Matkowsky, B.J., “Maximal energy accumulation in a superadiabatic filtration combustion wave,” *Combustion and Flame*, 118(1–2), 76-90, 1999.

Amaral, S.S., Andrade, J., Junior, D. C., Angélica, M., Costa, M., Gomes, T., Neto, S., Dellani, R., Henrique, L. and Leite, S., “Comparative study for hardwood and softwood forest biomass: chemical characterization, combustion phases and gas and particulate matter emissions Energy Department, Universidade Estadual Paulista, UNESP, Guaratinguetá Campus, Lumber Industrial Engin,” *Bioresour. Technol.*, vol. 164, no. x, pp. 55–63, 2014.

Barontini, F., Tugnoli, A., Cozzani, V., Tetteh, J., Jarriault, M. and Zinovik, I., “Volatile products formed in the thermal decomposition of a tobacco substrate,” *Industrial and Engineering Chemistry Research*, 52, 14984-14997, 2013.

Baker R. R. and Kilburn, K. D., “The Distribution of Gases within the Combustion Coal of a Cigarette,” *Beiträge zur Tab. / Contrib. to Tob. Res.*, vol. 7, no. 2, 1973.

Baker, R. R., “Variation of the Gas Formation Regions within a Cigarette Combustion Coal during the Smoking Cycle,” *Beitrage zur Tab. Int. Contrib. to Tob. Res.*, vol. 11, no. 1, pp. 1–17, 1981.

Baker, R. R., “A Review of Pyrolysis Studies to Unravel Reaction Steps in Burning Tobacco,” *Journal of Analytical and Applied Pyrolysis*, 11, 555-573, 1987.

Baker R. R. and Bishop, L. J., “The pyrolysis of tobacco ingredients,” *J. Anal. Appl. Pyrolysis*, vol. 71, no. 1, pp. 223–311, 2004.

Baker, R. R. and Bishop, L. J., “The pyrolysis of non-volatile tobacco ingredients using a system that simulates cigarette combustion conditions,” *J. Anal. Appl. Pyrolysis*, vol. 74, no. 1–2, pp. 145–170, 2005.

Baker, R. R., Coburn, S., Liu, C. and Tetteh, J., “Pyrolysis of saccharide tobacco ingredients: A TGA-FTIR investigation,” *J. Anal. Appl. Pyrolysis*, vol. 74, no. 1–2, pp. 171–180, 2005.

Baker, R. R., “Smoke generation inside a burning cigarette: Modifying combustion to develop cigarettes

that may be less hazardous to health," *Prog. Energy Combust. Sci.*, vol. 32, no. 4, pp. 373–385, 2006.

Bar-Ilan, A., Rein, G., Fernandez-Pello, A. C., Torero, J. L. and Urban, D. L., "Forced forward smoldering experiments in microgravity," *Exp. Therm. Fluid Sci.*, vol. 28, no. 7, pp. 743–751, 2004.

Barontini, F., Tugnoli, A., Cozzani, V., Tetteh, J., Jarriault, M. and Zinovik, I., "Volatile products formed in the thermal decomposition of a tobacco substrate," *Industrial and Engineering Chemistry Research*, 52, 14984-14997, 2013.

Bergman, P.C.A., Boersma, A.R., Kiel, J.H.A., Prins, M.J., Ptasiński, K.J., Janssen, F.J.J.G., "Torrefaction for entrained-flow gasification of biomass," Report - ECN-C--05-067, Petten, The Netherlands: ECN, 2005.

Bertschi, I., "Trace gas and particle emissions from fires in large diameter and belowground biomass fuels," *J. Geophys. Res.*, vol. 108, no. D13, p. 8472, 2003.

Betchen, L., Straatman, A.G. and Thompson, B.E., "A Nonequilibrium Finite-Volume Model for Conjugate Fluid/Porous/Solid Domains," *Numerical Heat Transfer, Part A: Applications*, 49:6, 543-565, 2006.

Black, R. R., Aurell, J., Holder, A., George, I. J., Gullett, B. K., Hays, M. D., Geron, C. D. and Tabor, D., "Characterization of gas and particle emissions from laboratory burns of peat," *Atmos. Environ.*, vol. 132, pp. 49–57, 2016.

Britt, P. F., Buchanan, A. C., Kidder, M. K. and Owens, C. V., "Influence of steroid structure on the pyrolytic formation of polycyclic aromatic hydrocarbons," *J. Anal. Appl. Pyrolysis*, vol. 66, no. 1–2, pp. 71–95, 2003.

Britt, P. F., Buchanan, A. C. and Owens, C. V., "Mechanistic investigation into the formation of polycyclic aromatic hydrocarbons from the pyrolysis hydrocarbons from the pyrolysis of terpenes," *Prepr, Pap., Am. Chem.Soc., Div. Fuel Chem*, vol. 49, no. 2001, pp. 868–871, 2004.

Burton, H. R., "Thermal Decomposition of Tobacco: V. Influence of Temperature on the Formation of Carbon Monoxide and Carbon Dioxide," *Beiträge zur Tab. / Contrib. to Tob. Res.*, vol. 8, no. 2, 1975.

Chao, C. Y. H. and Wang, J. H., "Comparison of the Thermal Decomposition Behavior of a Non-Fire Retarded and a Fire Retarded Flexible Polyurethane Foam with Phosphorus and Brominated Additives," *J. Fire Sci.*, vol. 19, no. 2, pp. 137–156, 2001.

Chen, L. W. A., Moosmüller, H., Arnott, W. P., Chow, J. C., Watson, J. G., Susott, R. A., Babbitt, R. E., Wold, C. E., Lincoln, E. N. and Wei, M. H., "Emissions from laboratory combustion of wildland fuels: Emission factors and source profiles," *Environ. Sci. Technol.*, vol. 41, no. 12, pp. 4317–4325, 2007.

Debenest, G., Mourzenko, V.V. and Thovert, J-F., "Smoldering in fixed beds of oil shale grains. A three-dimensional microscale numerical model," *Combustion Theory and Modelling*, 9(1), 113-135, 2005.



Debenest, G., Mourzenko, V.V. and Thovert, J-F., "Three-dimensional microscale numerical simulation of smoldering process in heterogeneous porous media," *Combustion Science and Technology*, 180(12), 2170-2185, 2008.

Deglise X., Richard C., Rolin A., François H., "Fast pyrolysis/gasification of lignocellulosic materials at short residence time," *Energy from biomass, First conference*, 1980(a).

Deglise X., Morlière P., Schlicklin P. "Mass and energy balances for a two fluidised bed pilot plant which operates on wood fast pyrolysis," *Energy from biomass, First conference*, pp. 569-573, 1980(b).

Deglise X. "Les conversions thermochimiques du bois *Revue Forestière Française*," vol.4 pp. 249-270, 1982.

Di Blasi, C., "Mechanisms of two-dimensional smoldering propagation through packed fuel beds," *Combustion Science and Technology*, 106(1-3), 103-124, 1995.

Dhargalkar, P.H. and Goldbach, K., "Control of Heavy Metal Emissions from Waste Incinerators, in *Control and Fate of Atmospheric Trace Metals*," J.M. Pacyna and B. Ottar, Editors. 1989, Springer Netherlands: Dordrecht. p. 33-45, 1989.

Dosanjh, S., Peterson, J., Fernandez-Pello, A.C. and Pagni, P.J. "Buoyancy effects on smoldering combustion," *Acta Astronautica*, 13(11), 689-696, 1986.

Einhorn-Stoll, U., Kunzek, H. and Dongowski, G., "Thermal analysis of chemically and mechanically modified pectins." *Food Hydrocolloids*, 21: 1101-1112, 2007.

Fatehi, M. and Kaviany, M. "Adiabatic reverse combustion in a packed bed," *Combustion and Flame*, 99(1) 1-17, 1994.

Font, R., Fullana, A., Caballero, J.A., Candela, J. and Garcia, A., "Pyrolysis study of polyurethane," *J. Anal. Appl. Pyrolysis*, vol. 58-59, pp. 63-77, 2001.

Fortsch D., Kluger F., Schnell U., Spliethoff H., Hein K. R. G., "A kinetic model for the prediction of NO emissions from combustion of pulverized coal," 27<sup>th</sup> international symposium on combustion, The Combustion Institute, pp3037-3044, 1998.

Garrido, M. A. and Font, R., "Pyrolysis and combustion study of flexible polyurethane foam," *J. Anal. Appl. Pyrolysis*, vol. 113, pp. 202-215, 2015.

Glarborg P., Alzueta, Dam-Johansen & Miller J. A., "Kinetic modeling of hydrocarbons/nitric oxide interactions in a flow reactor," *Combustion and Flame*, Vol. 115, pp. 1-27, 1998.

Goel, S., Sarofim, A., Kilpinen, P. and Hupa, M., "Emissions of nitrogen oxides from circulating fluidised bed combustors : modeling results using detailed chemistry," 27<sup>th</sup> international symposium on combustion, The Combustion Institute, pp3317-3324, 1998.

Gómez-Siurana, A., Marcilla, A., Beltrán, M., Berenguer, D., Martínez-Castellanos, I. and Menargues,

S., "TGA/FTIR study of tobacco and glycerol–tobacco mixtures," *Thermochimica Acta*, 573, 146–157, 2013.

Hadden, R.M., Scott, S., Lautenberger, C. and Fernandez-Pello, A.C., "Ignition of Combustible Fuel Beds by Hot Particles: An Experimental and Theoretical Study," *Fire Technology*, 47, 341–355, 2011.

Hadden, R.M., Rein, G. and Belcher, C.M., "Study of the competing chemical reactions in the initiation and spread of smouldering combustion in peat," *Proceedings of the Combustion Institute*, 34(2), 2547–2553, 2013.

Hays, M.D., Geron, C.D., Linna, K.J., Smith, N.D. and Schauer, J.J., "Speciation of gas-phase and fine particle emissions from burning of foliar fuels," *Environ. Sci. Technol.*, vol. 36, no. 11, pp. 2281–2295, 2002.

He, F., Yi, W., Li, W., Zha, J. and Luo, B., "Effects of fuel properties on the natural downward smoldering of piled biomass powder: Experimental investigation," *Biomass and Bioenergy*, vol. 67, pp. 288–296, 2014.

Huang, X. and Rein, G., "Smouldering combustion of peat in wildfires: Inverse modelling of the drying and the thermal and oxidative decomposition kinetics," *Combustion and Flame*, 161(6), 1633–1644, 2014.

Huang, X., Rein, G. and Chen, H. "Computational smoldering combustion: Predicting the roles of moisture and inert contents in peat wildfires," *Proceedings of the Combustion Institute*, 35(3), 2673–2681, 2015.

Huang, Y., Fan, C., Han, X. and Jiang, X., "A TGA-MS investigation of the effect of heating rate and mineral matrix on the pyrolysis of kerogen in oil shale," *Oil Shale*, vol. 33, no. 2, pp. 125–141, 2016.

Huang, X. and Rein, G. , "Thermochemical conversion of biomass in smouldering combustion across scales: The roles of heterogeneous kinetics, oxygen and transport phenomena," *Bioresource Technology*, 207, 409–421, 2016(a).

Huang, X. and Rein, G. "Interactions of Earth's atmospheric oxygen and fuel moisture in smouldering wildfires," *Science of the Total Environment*, 572, 1440–1446, 2016(b).

Karayildirim, T., Yanik, J., Yuksel, M. and Bockhorn, H., "Characterisation of products from pyrolysis of waste sludges," *Fuel*, vol. 85, no. 10–11, pp. 1498–1508, 2006.

Kee R. J., Rupley F. M., Meeks E. & Miller J. A., "Chemkin-III : a fortran chemical kinetics package for the analysis of gas-phase chemical and plasma kinetics," Sandia Report, n° 96-8216, 1996.

Kelley, M.L. and Schult, D.A., "Modeling extinction in forced opposed-flow smolder," *Combustion Theory and Modelling*, 10(1), 133–143, 2006.

Kinsman, L., Torero, J.L., Gerhard, J.I., Organic liquid mobility induced by smoldering remediation, *Journal of Hazardous Materials*, 325, 101–112, 2017.

Kissinger, H.E., "Reaction Kinetics in Differential Thermal Analysis," *Analytical Chemistry*, 29, 11, 1702-1706, 1957.

Koshland C., "Impact and control of air toxics from combustion," 26<sup>th</sup> international symposium on combustion, The Combustion Institute, pp. 2049-2065, 1996.

Leach, S.V., Ellzey, J.L. and Ezekoye, O.A., "A numerical study of reverse smoldering," *Combustion Science and Technology*, 130(1-6), 247-267, 1997.

Leach, S.V., Rein, G., Ellzey, J.L. Ezekoye, O.A. and Torero, J.L., "Kinetic and fuel property effects on forward smoldering," *Combustion and Flame*, 120(3), 358, 2000.

Lighty J.S. et Vernath J.M., "The role of research in practical incineration systems – a look at the past and the future," 27<sup>th</sup> international symposium on combustion, The Combustion Institute, pp. 1255-1273, 1998.

Lobert, J., Scharffe, D., Hao, W. M., Kuhlbusch, T. A., Seuwen, R., Warneck, P. and Crutzen, P.J., "Experimental evaluation of biomass burning emissions: Nitrogen and carbon containing compounds," *Global biomass burning. Atmospheric, climatic, and biospheric implications*. pp. 289–304, 1991.

Lutz A. E., Kee R. J., Grcar J. F., Rupley F. A., "OPPDIF : a fortran program for computing opposed flow diffusion flames," Report n°96-824, Sandia National Laboratories, 1997.

Martins, M.F., Salvador, S., Thovert, J.F. and Debenest, G., "Co-current combustion of oil shale - Part 2: Structure of the combustion front," *Fuel*, vol. 89, no. 1, pp. 133–143, 2010(a).

Martins, M.F., Salvador, S., Thovert, J.F. and Debenest, G., "Co-current combustion of oil shale - Part 1: Characterization of the solid and gaseous products," *Fuel*, vol. 89, no. 1, pp. 144–151, 2010(b).

McKenzie, L. M., Hao, W. M., Richards, G. N. and Ward, D.E. "Quantification of major components emitted from smoldering combustion of wood," *Atmos. Environ.*, vol. 28, no. 20, pp. 3285–3292, 1994.

Mckenzie, L. M., Hao, W. M., Richards, G. N. and Ward, D.E. "Air Toxins from Smoldering Combustion of Biomass," *Society*, vol. 29, no. 8, pp. 2047–2054, 1995.

McKenzie, L. M. "A Quantitative Investigation of Emissions from Smoldering Combustion of Biomass: Oxygen Containing Species and Halocarbons," University of Montana, 1996.

Monhol, F. A. F. and Martins, M. F. "Cocurrent Combustion of Human Feces and Polyethylene Waste," *Waste and Biomass Valorization*, vol. 6, no. 3, pp. 425–432, 2015.

Moussa, N.A., Toong, T.Y. and Garris, C.A., "Mechanism of smoldering of cellulosic materials," *Symposium (International) on Combustion*, 16(1), 1447-1457, 1977.

Muraleedharan, T. R., Radojevic, M., Waugh, A. and Caruana, A. "Emissions from the combustion of peat: An experimental study," *Atmos. Environ.*, vol. 34, no. 18, pp. 3033–3035, 2000.

Muramatsu, M., Umemura, S., Ohta, K. and Okada, T., "Thermal Analysis of Tobacco on a View Point of Kinetic Approach" *Netsusokutei*, 6(4), 137-145, 1979.

Nordlund, M. and Kuczaj, A.K., "Modeling flow, heat and mass transfer in a porous biomass plug - when used in an electrically heated tobacco system," *Sixth International Conference on Porous Media and Its Applications in Science, Engineering and Industry*, ECI Digital Archives, June 2016(b).

Nordlund, M. and Kuczaj, A.K., "Modeling Aerosol Formation in an Electrically Heated Tobacco Product," *International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering*, Vol:10, No:4, 2016(b).

Oja, V., Hajaligol, M.R., Waymack, B.E., "The vaporization of semi-volatile compounds during tobacco pyrolysis," *Journal of Analytical and Applied Pyrolysis*, 76, 117–123, 2006.

Ohlemiller, T.J., Bellan, J. and Rogers, F., "A model of smoldering combustion applied to flexible polyurethane foams," *Combustion and Flame*, 36(C), 197-215, 1979.

Ohlemiller, T. J. and Lucca, D. A., "An experimental comparison of forward and reverse smolder propagation in permeable fuel beds," *Combust. Flame*, vol. 54, no. 1–3, pp. 131–147, 1983.

Ohlemiller, T.J., "Modeling of smoldering combustion propagation," *Progress in Energy and Combustion Science*, 11(4), 277-310, 1985.

Olsson, M. "Wheat straw and peat for fuel pellets-organic compounds from combustion," *Biomass and Bioenergy*, vol. 30, no. 6, pp. 555–564, 2006.

Orfão, J. J. M., Antunes, F. J. A. and Figueiredo, J. L., "Pyrolysis kinetics of lignocellulosic materials—three independent reactions model," *Fuel*, vol. 78, no. 3, pp. 349–358, 1999.

Pan, L., Dai, F., Li, G. and Liu, S. "A TGA/DTA-MS investigation to the influence of process conditions on the pyrolysis of Jimsar oil shale," *Energy*, vol. 86, pp. 749–757, 2015.

Park, Y.-K., "Analysis of the Electrically Heated Tobacco Product (EHTP) for Tobacco Combustion," Technical report, University of Seoul, 2015.

Pironi, P., Switzer, C., Gerhard, J.I., Rein, G. and Torero, J.L. "Self-sustaining smoldering combustion for NAPL remediation: Laboratory evaluation of process sensitivity to key parameters," *Environ. Sci. Technol.*, vol. 45, no. 7, pp. 2980–2986, 2011.

Pozzobon, V., Baud, G., Salvador, S. and Debenest, G., "Darcy Scale Modeling of Smoldering: Impact of Heat Loss," *Combustion Science and Technology*, 189(2), 340-365, 2017.

Rashwan, T.L. Gerhard, J.I. and Grant, G.P., "Application of self-sustaining smouldering combustion for the destruction of wastewater biosolids," *Waste Management*, 50, 201–212, 2016.

Rein, G., Lautenberger, C., Fernandez-Pello, A.C., Torero, J.L. and Urban, D.L., "Application of genetic algorithms and thermogravimetry to determine the kinetics of polyurethane foam in smoldering

combustion," *Combustion and Flame*, 146(1–2), 95-108, 2006.

Rein, G., Cleaver, N., Ashton, C., Pironi, P. and Torero, J. L., "The severity of smouldering peat fires and damage to the forest soil," *Catena*, vol. 74, no. 3, pp. 304–309, 2008.

Rein, G., Cohen, S., Simeoni, A., "Carbon emissions from smouldering peat in shallow and strong fronts," *Proceedings of the Combustion Institute*, 32, 2489–2496, 2009.

Robb, E. W., Johnson, W. R., Seligman, R. B. and Westbrook, J.J., "Model Pyrolysis - The Study of Cellulose," *Beitrage zur Tab. Int. Contrib. to Tob. Res.*, vol. 3, no. 9, pp. 597–604, 1966.

Rogaume, T., Jabouille, F., Auzanneau, M., Goudeau, J.C. and Torero, J.L., "The Effects of Different Airflows on the Formation of Pollutants During Waste Incineration," *Fuel*, 81, 2277-2288, 2002.

Rogaume, T., Auzanneau, M., Jabouille, F., Goudeau J.C. and J.L. Torero, "Computational Model to Investigate the Effects of Different Airflows on the Formation of Pollutants During Waste Incineration," *Combustion Science and Technology*, 175, 8, 2003.

Rogaume, T., Jabouille, F. and Torero, J. L., "Computational Model to Investigate the Mechanisms of NO<sub>x</sub> Formation During Waste Incineration," *Combustion Science and Technology*, 176, 5-6, 925-943, 2004.

Schult, D.A., Matkowsky, B.J., Volpert, V.A. and Fernandez-Pello, A.C., "Propagation and extinction of forced opposed flow smolder waves," *Combustion and Flame*, 101(4), 471-490, 1995.

Schulten, H.-R., Pyrolysis- Field Ionization Mass Spectrometry - A New Method for Direct, Rapid Characterization of Tobacco," *Beiträge zur Tabakforschung International*, 13, 219–227, 1986.

Seeman, J.I., Fournier, J.A., Paine III, J.B., and Waymack, B.E., The Form of Nicotine in Tobacco. Thermal Transfer of Nicotine and Nicotine Acid Salts to Nicotine in the Gas Phase, *Journal of Agriculture and Food Chemistry*, 47, 5133-5145, 1999.

Senneca, O., Chirone, R., Salatino, P., Nappi, L., "Patterns and kinetics of pyrolysis of tobacco under inert and oxidative conditions," *Journal of Analytical and Applied Pyrolysis*, 79: 227-233, 2007.

Sharma, R. K., Wooten, J. B., Baliga, V. L. and Hajaligol, M. R., "Characterization of chars from biomass-derived materials: Pectin chars," *Fuel*, vol. 80, no. 12, pp. 1825–1836, 2001.

Sorum L., Skreiberg O., Glarborg P., Jensen A., Dam Johansen K. D., "Formation of NO from combustion of volatiles from municipal solid wastes," *Combustion and Flame* vol. 123, pp195-212, 2001.

Strezov, V., Popovic, E., Filkoski, R.V., Shah, P. and Evans, T., Assessment of the Thermal Processing Behavior of Tobacco Waste," *Energy Fuels*, 26, 5930–5935, 2012.

Switzer, C., Gerhard, J. I., Pironi, P., Rein, G. and Torero, J. L., "Self-sustaining smouldering combustion: A novel remediation process for non-aqueous phase liquids in porous media," *Environ. Sci. Technol.*, vol. 43, no. 15, pp. 5871–5877, 2009.

Switzer, C., Pironi, P., Gerhard, J.I., Rein, G. and Torero, J.L., "Volumetric scale-up of smouldering remediation of contaminated materials," *J. Hazard. Mater.*, vol. 268, pp. 51–60, 2014.

Tissari, J., Lyyränen, J., Hytönen, K., Sippula, O., Tapper, U., Frey, A., Saarnio, K., Pennanen, A. S., Hillamo, R., Salonen, R. O., Hirvonen, M. R. and Jokiniemi, J. "Fine particle and gaseous emissions from normal and smouldering wood combustion in a conventional masonry heater," *Atmos. Environ.*, vol. 42, no. 34, pp. 7862–7873, 2008.

Tiwari, P. and Deo, M., "Compositional and kinetic analysis of oil shale pyrolysis using TGA-MS," *Fuel*, vol. 94, pp. 333–341, 2012.

Torero, J. L. and Fernandez-Pello, A.C., "Natural convection smolder of polyurethane foam, upward propagation," *Fire Saf. J.*, vol. 24, no. 1, pp. 35–52, 1995.

Torero, J. L. and Fernandez-Pello, A. C., "Forward Smoldering of Polyurethane Foam in a Forced Air Flow," *Combustion and Flame*, 106 (1-2), 89-109, 1996.

Tumuluru, J.S., Sokhansanj, S., Hess, J. R., Wright, C.T. and Boardman, R.D. "A review of biomass torrefraction process and product properties for energy applications," *Industrial biotechnology*, 7(5): 384-401, 2011.

Van Kuijk, H., Van Oijen, J., Bastiaans, R. and De Goey, P., "Reverse combustion: Kinetically controlled and mass transfer controlled conversion front structures," *Combustion and Flame*, 153(3) 417-433, 2008.

Varhegyi, G., Czegeny, Z., Jakab, E., McAdamb, K. and Liu, C., "Tobacco pyrolysis. Kinetic evaluation of thermogravimetric–mass spectrometric Experiments," *Journal of Analytical and Applied Pyrolysis*, 86, 310–322, 2009.

Wang, X., Wang, Z., Dai, Y., Ma, K., Zhu, L. and Tan, H., "Thermogravimetric study on the flue-cured tobacco leaf pyrolysis and combustion using a distributed activation energy model," *Asia-Pacific Journal of Chemical Engineering*, 12: 75–84, 2017.

Werner, K. Pommer, L. and Broström, M., "Thermal decomposition of hemicelluloses" *Journal of Analytical and Applied Pyrolysis*, 110: 130-137, 2014.

Werther, J. and Ogada, T., "Sewage sludge combustion," *Progress in Energy and Combustion Science*, 25(1): p. 55-116, 1999.

Xu, T. and Huang, X., "Study on combustion mechanism of asphalt binder by using TG-FTIR technique," *Fuel*, vol. 89, no. 9, pp. 2185–2190, 2010.

Yang, C., Thovert, J-F. and Debenest, G. "Upscaling of mass and thermal transports in porous media with heterogeneous combustion reactions," *International Journal of Heat and Mass Transfer*, 84, 862-875, 2015(b).

Yang, H., Yan, R., Chen, H., Lee, D.H. and Zheng, C. "Characteristics of hemicellulose, cellulose and lignin

pyrolysis," *Fuel*, 86: 1781-1788, 2007.

Yang, J., Chen, H. and Liu, N., "Heat Loss and Kinetic Effects on Extinction and Critical Self-Sustained Propagation of Forced Forward Smoldering," in: K. Harada, K. Matsuyama, K. Himoto, Y. Nakamura, K. Wakatsuki (Eds.) *Fire Science and Technology: The Proceedings of 10th Asia-Oceania Symposium on Fire Science and Technology*, Springer Singapore, Singapore, 2017, pp. 831-840, 2015(a).

Yang, J., Chen, H. and Liu, N., "Modeling of Two-Dimensional Natural Downward Smoldering of Peat," *Energy & Fuels*, 30(10), 8765-8775, 2016.

Yerman, L. Wall, H. and Torero, J.L., Experimental investigation on the destruction rates of organic waste with high moisture content by means of self-sustained smoldering combustion, *Proceedings of the Combustion Institute*, Volume 36, Issue 3, Pages 4419-4426, 2017.

Yokelson, R. J., Susott, R., Ward, D. E., Reardon, J. and Griffith, D. W. T., "Emissions from smoldering combustion of biomass measured by open-path Fourier transform infrared spectroscopy," *J. Geophys. Res.*, vol. 102, no. D15, p. 18865, 1997.

Zanoni, M.A.B., Torero, J.L. and Gerhard, J. I., "Determination of the interfacial heat transfer coefficient between forced air and sand at Reynold's numbers relevant to smoldering combustion," *International Journal of Heat and Mass Transfer*, Volume 114, Pages 90-104, 2017.

Zhang, Y., Shao, Y., Lin, Y., Luan, S., Mao, N., Chen, W. and Wang, M., "Emission inventory of carbonaceous pollutants from biomass burning in the Pearl River Delta Region, China," *Atmos. Environ.*, vol. 76, no. 0, pp. 189-199, 2012.

Zhou, S., Ning, M., Xu, Y., Hu, Y., Shu, J., Wang, C., Ge, S., Tian, Z., She, S., He, Q., "Thermal degradation and combustion behavior of reconstituted tobacco sheet treated with ammonium polyphosphate," *Journal of Analytical and Applied Pyrolysis*, 100, 223-229, 2013.

## 11 APPENDIX

**Table 27 Technology readiness level (adapted from NASA and the European Commission)**

| TRL | Description                                 |
|-----|---|
| 9   | Market competition / widespread application |
| 8   | Multiple commercial applications            |
| 7   | Technology integrated at full-scale         |

|          |   |
|----------|---|
| <b>6</b> | <b>Technology demonstrated in operational environment</b> |
| <b>5</b> | <b>Technology validated at demonstration scale</b>        |
| <b>4</b> | <b>Technology validated at pilot-scale</b>                |
| <b>3</b> | <b>Technology validated in the lab</b>                    |
| <b>2</b> | <b>Concept formulated and experimental proof</b>          |
| <b>1</b> | <b>Basic technology research</b>                          |

