Soil Thermal Weeding.

University of Canterbury,
Dept. of Mechanical Engineering,
Final Year Project, and
Higher Temperature & Duration Seed Treatment.

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The BHU Future Farming Centre

Permanent Agriculture and Horticulture Science and Extension

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1. Acknowledgments and thanks

The majority of the research presented in this report has been undertaken by other people, and their hard work and dedication is very much appreciated.

Thanks to the four students, Daniel Smithies, Jarrod Tucker, Joseph Towers, and Thomas McRobie of the University of Canterbury (UoC) Dept. of Mechanical Engineering, who undertook the final year student project to build the proof of concept soil heating cooling system as well as Hamish Loader, a fellow student, who took up the baton of Daniel, Jarrod, Joseph and Thomas' work, and completed the system, first via a summer scholarship, and then as a casual job. Prof. Mark Jermey and Dr Paul Zwaan of the Dept. of Mechanical Engineering for setting up the student project, and especially Mark for ensuring the project was finished through Hamish's scholarship and employment. A particular thanks to AGMARDT who not only funded all of the project, but, who were most understanding and tolerant of the significant extra time it took to complete.

Thanks to Arthur Bluon, a French intern at the FFC in 2015, who undertook all the seed heating experiments, with commitment, interest and great attention to detail. Arthur also undertook a wide range of other experiments for the FFC.

2. Summary

This report covers:

- Two seed heating experiments studying the effect of higher temperatures and longer durations on seed mortality plus the effect of seed moisture on seed mortality.
- The results of the University of Canterbury, Dept. of Mechanical Engineering's final year student project to build a proof-of-concept soil heating and cooling system, along with an initial test of its effect on the weed seed bank.

2.1. Seed heating experiments

- Mustard seeds were used instead of weed seed containing soil for the experiments to simplify the methods. Seeds were heated in an insulated retort powered by electric hot air guns.
- In the first experiment seeds were heated at temperatures of 100°C, 200°C, and 400°C for a range of durations up to nearly ten minutes.
    - The results clearly showed that at 100°C (the maximum seed temperature steam can achieve) even with long treatment durations (> 10 minutes) 100% seed mortality was not achieved.
    - In comparison, complete seed mortality was achieved in 26 seconds at 200°C and 10 seconds at 400°C.
    - To achieve high levels of seed mortality in sufficiently short durations, e.g., < 30 seconds, temperatures higher than 100°C are required.
    - Further research using soil with real weed seeds is required to determine the optimum temperature × treatment duration, to inform the design of a field soil thermal weeder.
- The second experiment compared mortality rates on 'dry' seeds from their packet and 'moist' seeds that had been imbibed for 24 hours.
    - Surprisingly the moist seeds were more resistant to treatment, but, ultimately all seeds were killed.
    - The use of mustard seeds imbibed for 24 hours is now not considered a realistic substitute for real weed seeds that have been in moist or dry soil for weeks or months. Further work is therefore required using weed seed containing soil that is then kept dry or moist for several weeks or months is required.

2.2. UoC final year project: Proof of concept, heat recycling, soil heating system

- The University of Canterbury (UoC), Dept. of Mechanical Engineering (DME), Student Final Year Project, theoretically analysed the heat recycling concept and constructed a proof of concept soil heating system.
- Four different heating approaches were considered: microwaves; parallel pillow plates; 'buckets'; and Vertical sections. Only the vertical sections concept was considered viable.
- A theoretical analysis of the potential heat recovery showed that with a three section system 50% heat recovery was possible, increasing to 86% with a 13 section system. Even greater heat recovery is considered achievable with a continual flow system as conceived in the previous desk study reports. However, at ~80% heat recovery it is considered that the fuel reductions, compared with the current non-heat recovery steam systems, is sufficient to make soil thermal weeding economically viable in horticultural crops.
- The students constructed a proof of concept prototype, which, proved a significantly greater challenge than both academic staff and the students anticipated. After the challenges were overcome, the heating system was completed and tested with weed seed containing soil.
- Germination tests of the treated soil showed that nearly all weed seeds had been killed by the treatment. However, temperature measurements indicated the heat recycling system was not working as efficiently as expected, presumably due to the difficulty of effectively insulating the system, particularly the fans, such that there was significant heat loss during air transfer.
- Despite the challenges, the project is considered highly valuable in moving the soil thermal weeding with heat recycling concept forward. The concept has survived an independent critical analysis and confirmed that high levels of heat / energy recycling can be achieved.

2.3. Overall conclusions

- To inform the design parameters of a continual flow heat exchanger, the optimum temperature at which rapid (< 30 seconds) weed seed mortality can be achieved in soil still need to be accurately determined, but, it is considered likely to be between 150°C and 300°C.
- The impact on seed death of weed seeds in soil that is 'moist' vs. dry also needs to be established. Moist soil also has greater mass due to the presence of the water, which, will also evaporate at the > 100°C temperatures need for rapid seed mortality, which will impact the functioning of the heat exchangers, so a better understanding of the role of water in the heat treatment system is also required.
- The thermodynamics and engineering concepts proposed in Merfield (2013a) are viable, but, that to achieve the highest possible levels of heat recycling a continual flow heat exchanger system is required.
- Once optimum temperature and the impacts of soil moisture are better understood a large-scale, laboratory based, continual flow, heating and cooling system, needs to be built to test the engineering and seed killing ability. This should then lead onto a full scale, tractor mounted, prototype.

3. Part one: Higher temperature seed mortality tests and the effect of seed moisture

3.1. Introduction

Previous laboratory research (Merfield, 2013a), using a simple bench top heating retort, studied a range of factors impacting effective soil thermal weeding, including comparing steam with hot air as the heat transfer medium, the effects of temperature, soil texture, aggregate size, soil moisture content and the interaction of heating time on seed mortality. While the research aimed to fill the gaps in the existing literature (see Merfield, 2013a) it became clear, as the concept of soil thermal weeding with hot air and heat recycling, was progressed, especially in terms of machinery design, gaps still existed, mainly the effect of higher temperature (>100°C) hot air on the speed of seed mortality and the effect of seed moisture content on seed mortality when heated by air.

With steam based soil thermal weeding, a range of research has been undertaken on seed mortality (see Merfield (2013a) for details) so the effect of steam on seed mortality in soil thermal weeding is relatively well understood, however, there is less research looking at hot air based soil thermal weeding, and particularly heat recycling systems which cool the soil post treatment. There are three key things that differ between steam and hot air systems:

1. Due to the laws of physics, steam treated soil has a maximum temperature of 100°C i.e., the boiling temperature of water, but in practice it is lower due to heat loss, e.g., a maximum of 90°C, while there is no theoretical upper limit for hot air (although there are clearly practical limits).
2. Steam by its nature increases the water content of the soil, often bringing it close to field capacity. As discussed in Merfield (2013a) moisture has multiple effects, including effecting seeds resistance to heating, with moist seeds being considered more susceptible. Hot air has the opposite effect of drying the soil, so it will also dry the seeds and may make them less susceptible.
3. In steam systems there is no heat recovery so the heated strip of soil remains at elevated temperatures often for tens of minutes until it cools to ambient. This long duration is critical to achieving high rates of weed mortality due to the sub 100°C temperatures (as discussed above). In the proposed hot air recycling systems, the soil will be cooled down to reclaim the heat so therefore the soil and seeds within it will be heated for a much shorter duration.

Two further experiments were therefore conducted. The first looked at the effect of much higher temperatures (100°C to 400°C) to determine what temperature is required in a hot air soil thermal weeding system with heat recycling, to keep treatment times sufficiently short, e.g., <30 seconds. The second experiment looked at the effect of seed moisture content on seed mortality.

3.2. Methods

3.2.1. Treatment equipment and general methods

The treatment system is the same as (Merfield, 2013a, page 65) and is fully described there, but in brief, a heating retort was constructed from a steel pipe 155 mm diameter, placed in an insulated container, with hot air piped into the bottom from two hot air guns (Bosch PHG 630 DCE, 2000 W) on which the output temperature could be set. The actual treatment temperature was measured using a digital thermometer reading the retort temperature and the heat setting on the air gun was adjusted to achieve the desired temperature.

A treatment 'basket' was constructed from stainless steel mesh, in the form of a cylinder closed at one end, that fitted snugly inside the retort, such that all the air flowing through the retort flowed through the basket, which could also be easily inserted and removed from the retort, thus allowing seeds to be quickly placed into and removed from the hot air stream. To cool the seeds immediately post treatment, ambient air was sucked through the basket for 20 seconds, using a custom system described in (Merfield, 2013a, page 66).

After treatment seeds were placed in clear, polypropylene, food grade, trays 15 cm × 10 cm × 3 cm L × W × H, on four paper serviette towels that had been dampened (barely moist, not wet) and placed in the bottom of the tray, and sealed with a water tight lid. Trays were then placed in a controlled environment room, with a minimum temperature set at 15°C and a maximum of 30°, with fluorescent lights on a 16 hour day and 8 hour night cycle. Germinated seeds were counted at 7 and 14 days.

Mustard (*Sinapis alba*) seeds were used for both experiments. Seeds rather than soil containing weed seeds was used to simplify the experimental requirements: The numbers of seeds in soil are variable and unpredictable meaning larger amounts of soil are required to achieve sufficient statistical power. Most weed seeds are dormant, so, extended germination durations are required, e.g., potentially several months. In comparison, as a crop species, mustard has limited dormancy so they germinate readily. Mustard was chosen as it is readily available, the seeds are comparatively large compared with most weed seeds (Roberts, 1982) and should therefore be harder to kill, so the results should underestimate the effects on smaller seeds, i.e., not give overly optimistic results. Finally, due to the large numbers of seeds required, the larger mustard seeds were easier to handle.

The thousand seed weight of the mustard seeds was determined using the method of Willan (1986), then the weight of the number of seeds required (200 Expt. 1, 100, Expt.2) was calculated from the thousand seed weight, and seeds lots were then weighed out to three decimal places. While this did not give the exact same number of seeds in each lot, it was considerably faster, and the variation in the number of seeds per lot was small, mean of 3.7 seeds per 200 seed lots based on counting the seeds in 10 lots. Not all seeds are viable, so, even where seeds are counted into lots, there is variability in the percentage emergence. In addition, pre trial testing was used to target the treatment durations such that the results would range from zero to complete seed mortality, therefore the statistical effect of the variation in the number of seeds per lot should be small compared with the large size of the treatment effects.

All results were analysed with ANOVA.

3.2.2. Experiment 1: Temperature × duration

The experiment was two factorial and studied the effect of three temperatures, 100°C 200°C and 400°C, over a range of durations, on seed mortality (Table 1), with a zero treatment duration being the control, i.e., seeds were not exposed to heat.

Table 1. Experiment 1 temperature and duration treatments

	Duration - seconds										
Temperature	**A (ctrl)**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**Interval**
100°C	0	60	121	182	243	304	365	426	487	548	61
200°C	0	5	12	19	26	33	40	47	54	61	7
400°C	0	1	2	3	4	5	6	10	15		Variable

The treatment duration differed among the treatment temperatures as pre trial testing showed that higher temperatures achieved seed mortality much faster, so, the durations were set in a range that aimed to achieve 100% mortality at the longest durations. Two hundred seeds were used in each treatment lot. There were three replicates.

Treatments were not fully randomised due to the time for the heating system to equilibrate at each temperature. Therefore all samples for a given temperature were treated in one batch, but, fully randomised within the batch. The order in which the treatment temperatures were chosen was randomised.

3.2.3. Experiment 2: Effect of seed moisture content

The experimental design was two factorial. First factor was seed moisture content with 'dry' vs. imbibed 'moist' seeds. The second factor was duration with seeds treated for 0, 60, 150, 240, 330, 420, 510, 600, 690, and 780 seconds. Treatment temperature was 100°C. It was aimed to test higher temperatures as well, but, resources did not permit this. There were three replicates.

Seeds were weighed out into lots of 100. Half the lots were randomly chosen then each placed in an individual germination tray with moist paper towels, as described above, for 24 hours prior to the experiment, to allow them to become fully imbibed. 'Dry' seeds, were at the ambient moisture content of the seed packet. Moisture content of the seeds was not measured, which was an oversight, but, 24 hours was considered a good duration to ensure that seed moisture content was as high as could be achieved, but before germination initiated, which, would result in a multitude of biochemical pathways being activated along with embryonic development, which it was considered would not be representative of dormant but ungerminated weed seeds in soil.

3.3. Results and discussion

3.3.1. Experiment 1: Temperature × duration

As the duration varied among the temperatures statistical comparisons were only undertaken within each temperature, not among temperatures. Percentage germination was calculated on the number of germinated seeds divided by 200, the estimated number of seeds per lot. Within each temperature there was a highly significant difference ($p<0.001$) in percentage germination at the different treatment durations, i.e., germination was close to 100% for untreated seeds and dropped to zero for 200°C and 400°C and ~10% for 100°C (Figure 1).

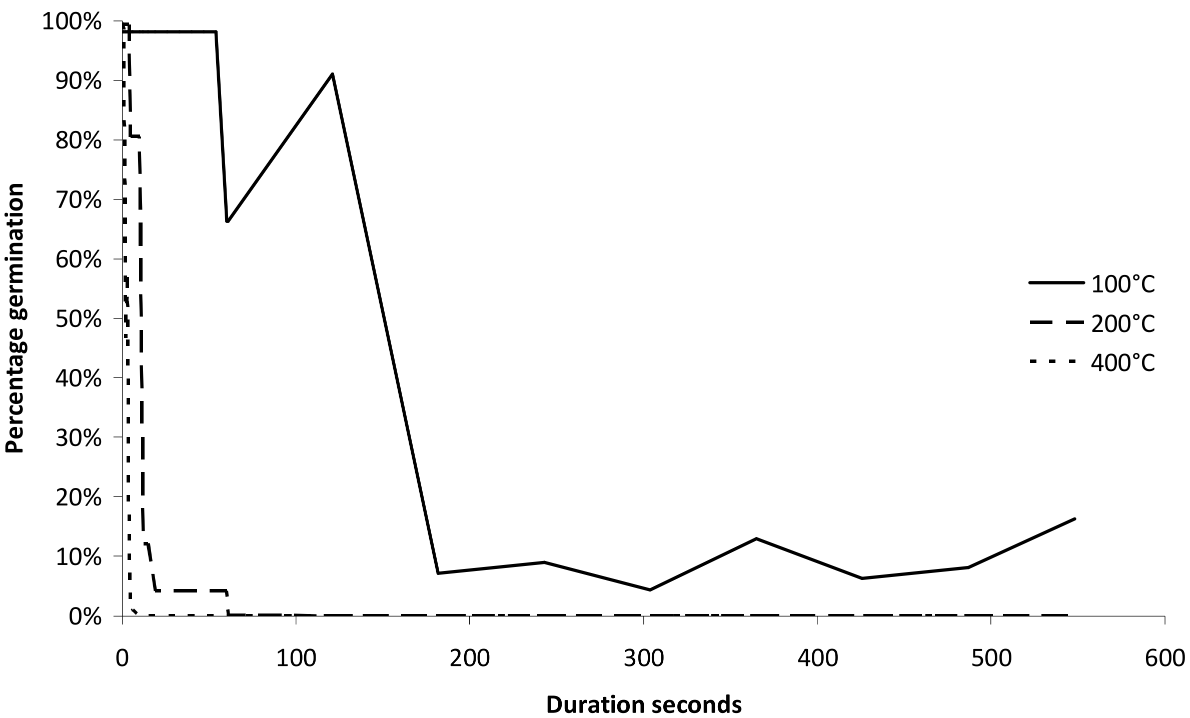

Figure 1. Decline in percentage germination of mustard seeds over time, at three treatment temperatures.

The decline in the germination rate at 200°C and 400°C was particularly rapid, with complete seed mortality achieved in 26 seconds at 200°C and 10 seconds at 400°C. In comparison, compete seed mortality was never achieved at 100°C, even after 548 seconds (9 minutes, 8 seconds). This is taken to indicate a step change in the speed at which seed mortality is achieved between 100°C and 200°C which is considered to be critical for soil thermal weeding. For example, an intrarow soil thermal weeder, treating 7 × 7 cm intrarow 'slots', with four slots per tractor bed, requires substantial amounts of soil to be heated at the four speeds listed in Table 2.

Table 2. Volume of soil to be treated based on four, 7 × 7 cm intrarow 'slots' per tractor bed at four speeds.

Speed kph	**1**	**2**	**3**	**4**
Soil volume m^3 per minute	0.33	0.65	0.98	1.31
Soil volume litres per second	5.4	10.9	16.3	21.8

With a treatment temperature of 100°C a treatment duration in excess of 10 minutes would be required, meaning, at 4 kph, 10.3 m^3 of soil (1.31 m^3 × 10 minutes) would need to be within the treatment system, while at 400°C only 0.22 m^3 of soil (1.31 m^3 × (10/60) seconds) would need to be held (ignoring any extra seed mortality achieved during soil heating up and cooling down stages). With the bulk density of treated soil around 1.5 tonne / m^3 this equates to 15.5 tonnes of soil (10.3 m^3 × 1.5 t/m^3) at 100°C and 0.3 tonnes (0.22 m^3 × 1.5 t/m^3) at 400°C. To be practically viable, treatment temperatures clearly have to be significantly more than 100°C. However, higher temperatures have drawbacks, e.g., longer heat exchangers to allow for energy transfer, greater harm to soil biology, and at very high temperatures, e.g., > 400°C combustion of plant residues may occur. For example, in this experiment, at 400°C the mustard seeds started to char and also explode (pop). 400°C is therefore considered to be at the very upper limit of what is viable and that temperatures closer to 300°C are more likely to be the maximum in a practical heating system.

Further experiments are therefore required focusing on the 150°C to 300°C temperature range, using finer temperature increments, e.g., 50°C, to determine the optimum treatment temperature. In addition, while mustard was valuable in this experiment for simplifying and reducing the amount of work, mustard seed on its own is not representative of the weed seedbank in soil, so, future experiments need to use soil with naturally occurring seedbanks, to ensure that the results are sufficiently robust to inform the design of the soil thermal weeding heat exchanger systems.

3.3.2. Experiment 2: Effect of seed moisture content

The effect of seed moisture was the opposite of what was expected in that survival was higher in moist seeds than the dry seeds (germination means: moist = 25%, dry = 17%, $p<0.009$, LSD=0.055). However, the effect of duration was both as expected and highly significant, ($p<0.001$) with 98% germination for the control (zero treatment time) and zero survival at 690 seconds (11 minutes 30 seconds, Figure 2).

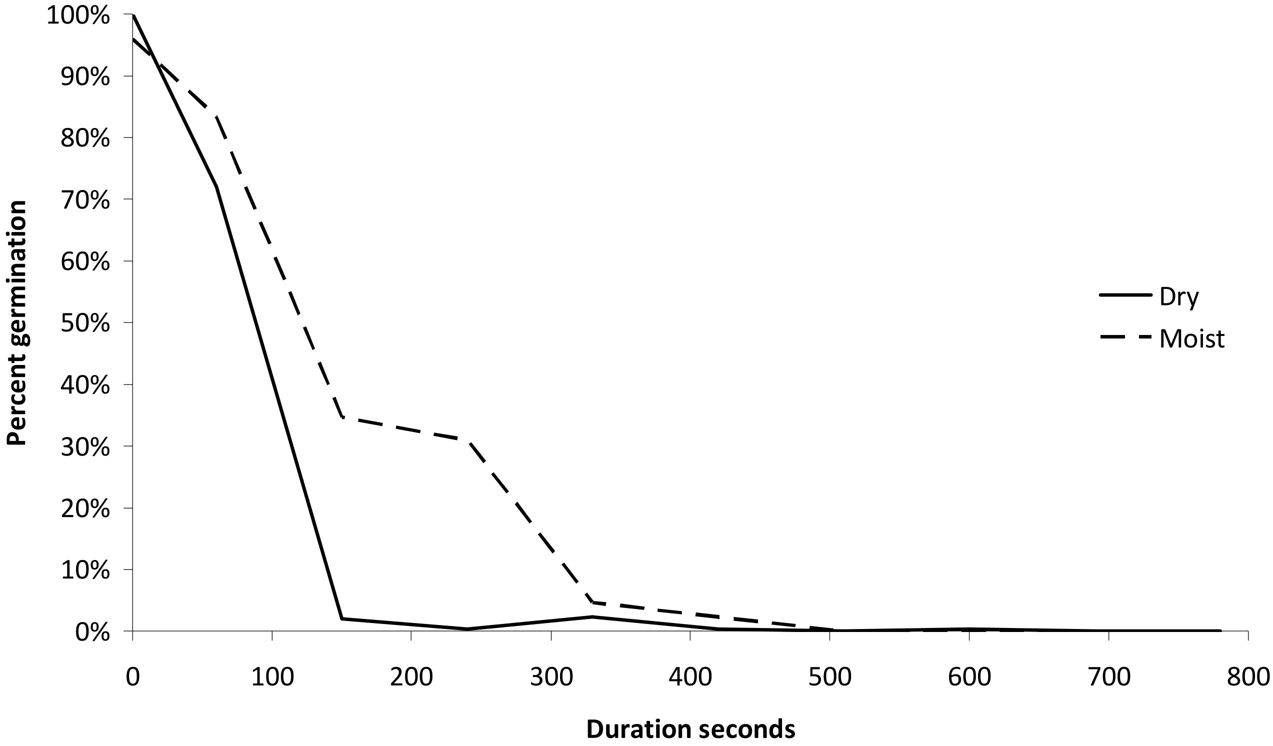

Figure 2. The effect of treatment duration on dry or imbibed (moist) mustard seeds heated to 100°C.

It was expected that moist seeds would be more susceptible to heat than dry, because research looking at heat treatment of seeds to manage seed borne diseases found water bath treatment durations of greater than 10 to 20 minutes at 50°C to 55°C reduced germination (Strandberg & White, 1989; Pryor *et al.*, 1994; Hermansen *et al.*, 1999) while hot air treatments at 70°C for 15 days of high quality carrot seed did not reduce germination or vigour (Trigo *et al.*, 1998). While a hot water bath is clearly different from heating imbibed seeds with hot air, the fact that imbibed seeds were more resistant to heat is still contrary to expectations. The reasons for this are unclear. One hypothesis is that the mass of the seeds was higher due to the imbibed water which meant that more energy was required to raise them to lethal temperatures. However, the seeds are comparatively small, and considering the significant flow of hot air around the seeds, any reduction in the rate of heating is thought to be small. A another difference, is that this experiment was using higher temperatures that the above experiments which are aimed at disinfesting seeds of pathogens, and that the effects of seed moisture on seed mortality at higher temperatures i.e., > 100°C is different than at lower, e.g., < 70°C. More research is therefore clearly required to understand this effect. However, while heating seeds without soil is considered sufficiently realistic for an initial study of the effect of temperature and duration, it is questioned if imbibing non-dormant crop seeds over 24 hours is a realistic comparison to weed seeds that may have been in wet soil for many months over winter, or dry soil for many months over summer. Further research on the effects of moisture on seeds should therefore, be undertaken using real weed seed banks in soil that has been kept moist and dry for an extended period prior to treatment.

It is therefore clear from both experiments, that, future research must use soil with naturally occurring seed banks.

4. Part two: UoC final year project: Proof of concept, heat recycling, soil heating system

4.1. Introduction

While the prior research that the FFC has undertaken on soil thermal weeding (STW) (Merfield, 2013a, 2013b, 2016) has shown the potential for using hot air instead of steam as the heat transfer medium, with the aim of dramatically reducing energy / fuel use, the concept had not been subjected to a more rigorous physical / thermodynamic analysis.

The University of Canterbury (UoC) Dept. of Mechanical Engineering (DME) was engaged, through their final year student project, to undertake a thermodynamic and engineering analysis of soil thermal weeding using hot air with heat recycling, and to build a proof of concept soil heating and cooling system to confirm the viability of the concept. This was funded by the Agricultural and Marketing Research and Development Trust (AGMARDT, agmardt.org.nz).

This report summarises the key finding of the DME work and also the results of a test of the soil heating and weed seed killing capabilities of the proof of concept system. The full project report is in the Appendix.

4.2. Final year project report key points

The four students: Daniel Smithies, Jarrod Tucker, Joseph Towers and Thomas McRobie, familiarised themselves with the concept of soil thermal weeding (STW) and some of the key issues, via the previous STW reports by the FFC (Merfield, 2013a, 2013b, 2016) as well as the physics and engineering literature on heat transfer in particulate solids. The core of their brief was the issue of heat recycling, or finding heating approaches to dramatically reduce energy / fuel consumption.

They developed four intial heat transfer concepts:

- Microwaves;
- Parallel pillow plates;
- 'Buckets';
- Vertical sections.

4.2.1. Microwaves

Microwaves had been suggested as a heating mechanism by a UoC academic, and microwaves have been investigated for weed control in the past, both for killing seeds and living plants (Diprose & Benson, 1984; Vela-Múzquiz, 1984; Barker & Craker, 1991; Nelson, 1996; Amista, 2002; Zanche *et al.*, 2003; Sartorato *et al.*, 2006; Brodie *et al.*, 2009; Brodie & Hollins, 2015; Brodie *et al.*, 2017; Khan *et al.*, 2018). To be effective for STW in terms of minimising energy consumption the microwaves need to differentially heat the seeds but not the soil, the same as in a domestic microwave oven where the food is heated but not the container the food is in. However, both theoretical analysis and simple tests heating soil in a domestic microwave oven, showed that selective heating is not possible, as it is the H-O bonds in water that microwaves heat, and as both soil and seeds contain water, often with soil containing more water on a weight for weight basis than seeds, microwaves therefore heated both soil and seeds, which would not result in energy savings. The production of kilowatt amounts of microwaves on a tractor based system also has a number of problems. Further, despite the decades of research on microwaves for weed control, both foliar and seed, no commercial machines have ever been made, which further indicates, the limited viability of microwaves for weed control.

4.2.2. Parallel pillow plates

Parallel pillow plate heat exchangers are used to heat a range of particulate solids by conduction, especially finely powdered solids (Figure 3).

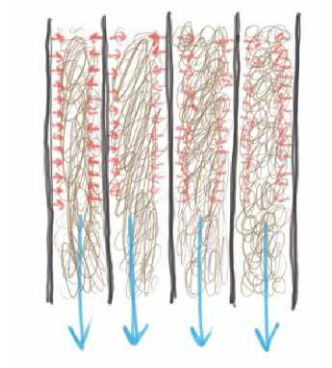

Figure 3. Sketch of the parallel plate concept from the students report. Blue arrows indicate the direction of soil flow and the small red arrows represent the heat transfer from the plates to the soil.

The pillows contain a fluid that transfers the heat into the soil, and, by having a second pillow plate heat exchanger after the first, to cool the soil down, the heat can be reclaimed from the soil. However, theoretical predictions of heat transfer showed that heat transfer by conduction was much slower than convection. There were also concerns that the small spaces between the pillow plates would clog with soil due to its sticky nature when moist / wet.

4.2.3. 'Buckets'

The buckets concept was based on a series of discreet containers- the 'buckets' - which held the soil, through which air was blown to transfer heat. The process worked by the central bucket being heated, and then once treated, it is moved along, and then air is passed through it to reclaim the heat in the soil, which is then passed through the bucket waiting to be heated, thus transferring heat, from the heated soil to preheat the soil waiting to be heated (Figure 4).

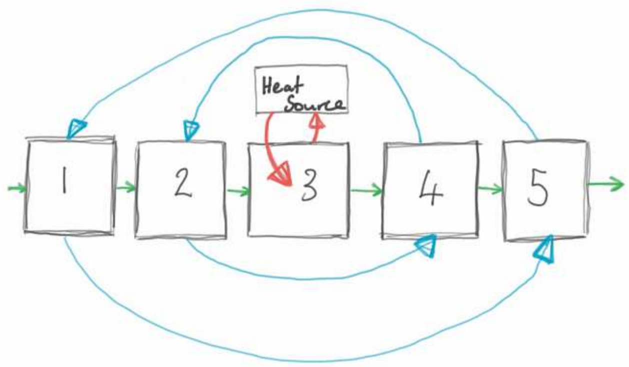

Figure 4. Sketch of the buckets concept from the students report. The blue arrows indicate the circulation of air between buckets, the red arrows represent the heat input into the centre bucket, and the green arrows show the direction that the buckets of soil will move along.

The bucket concept was abandoned, principally due to the complexity of the design.

4.2.4. Vertical sections

The vertical section concept made use of the bucket idea of compartmentalising the soil, but simplifying it into vertical sections so gravity would move the soil through the system - as in the pillow plates. The concept consists of a series of chambers arranged vertically with a shutter / gate between the sections that opens to allow the soil to progress down into the next chamber, with air being transferred between the different chambers to transfer the heat from the treated to untreated soil (Figure 5).

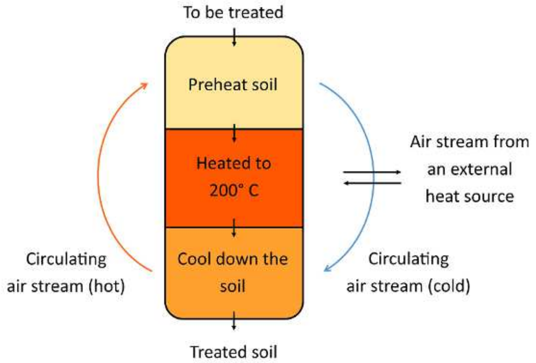

Figure 5. Diagram of the vertical sections concept from the students report. The red and blue arrows indicate the circulation of hot and cold air between the different sections, the horizontal arrows show the heat circulating between the heat source and middle section, the vertical arrows show the direction of soil flow.

This approach was considered to be the most practical from the perspective of building a prototype. Also, critically, by increasing the number of chambers, the percentage of heat recovered also increased. The students calculated the theoretical heat recovery for a range of number of chambers (Table 3).

Table 3. Percentage of heat recovered for a given number of chambers.

Number of chambers	**3**	**5**	**7**	**9**	**11**	**13**
Heat recovered	50%	67%	75%	80%	83%	86%

The highest level of heat recovery at 86% would be sufficient to make STW economically viable, for example, the 570 to 850 L·diesel·ha^{-1} currently used by steam based systems (Hansson & Svensson, 2004; Hansson & Svensson, 2007; Melander & Kristensen, 2011) would be reduced to 80 to 119 L diesel ha^{-1}. As the vertical sections concept uses discreet rather than a continual process, there is a practical limit on the number of sections and therefore a limit to the amount of heat recovered. However, in a continual process, i.e., a counterflow heat exchanger, efficiency of transfer close to 100% can be achieved, so the amount of energy / fuel required would be smaller again.

4.3. Prototype soil thermal heater

The students then built a prototype soil thermal heater based on the vertical sections concept (Figure 6).

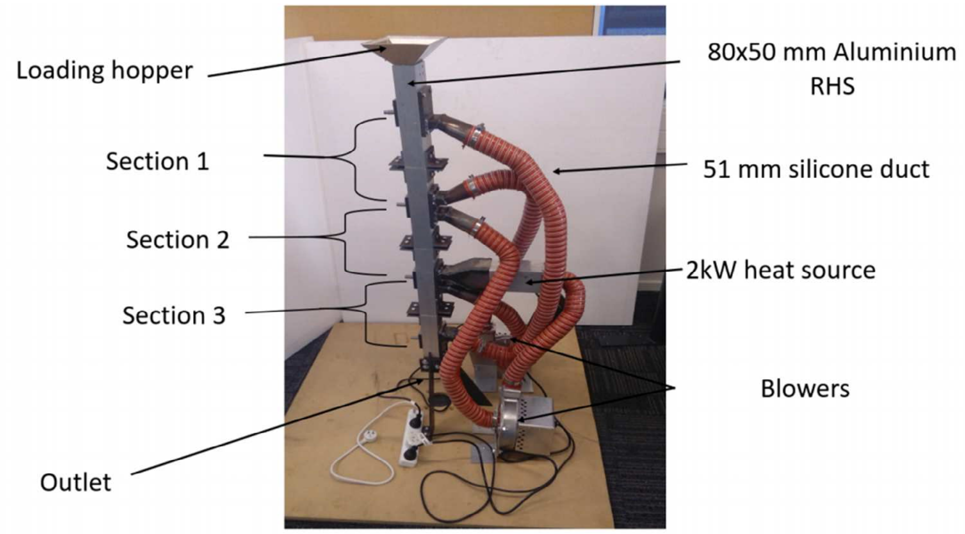

Figure 6. Prototype device before insulation was installed, from the students report.

The air transfer system had the hot air source directly entering the middle chamber, and was recirculated back into the middle chamber via the heater to maximise the temperature of the soil in the middle chamber. The air exiting the bottom chamber, where the soil is being cooled, took the heat and transferred it to the top chamber where the soil was being pre-heated. That air having transferred its heat into the soil in the top chamber was then had then ducted into the soil in the bottom chamber to continue cooling it down (Figure 7).

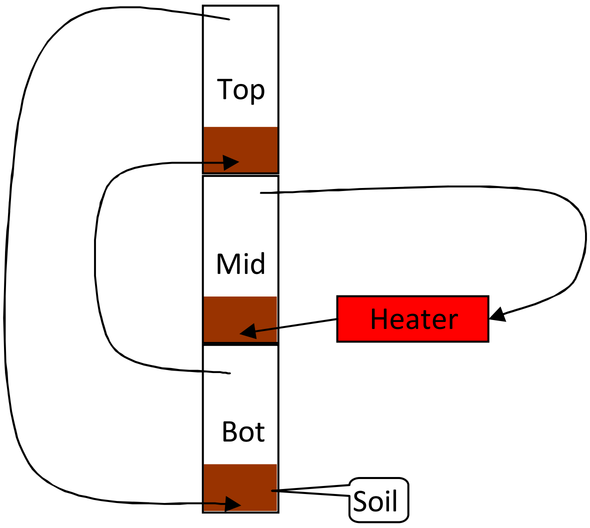

Figure 7. Schematic of the airflow through the heating system.

Building the heating system proved a considerably larger challenge than both students and staff expected. A key problem was finding fans that could circulate the hot air at the required volumes and pressures, because the temperature of the air was too hot for plastic fans so metal fans were required, which are much less common. The fan to circulate air through the central and hottest chamber was a particular problem as temperatures as high as 200°C were being targeted. This resulted in a custom designed fan being built by the summer scholarship student, Hamish Loader, who also completed testing of the system. Fundamentally the fans required are not out of the ordinary in terms of pressure and air flow. For a commercial machine, fans can simply be designed and built to required specification. However, for the timeframe and financial limitations of the student project using off-the-shelf componentry was optimal.

There were also a number of other challenges that the students faced and successfully addressed, such as the designing and building the gate mechanisms to hold and drop the soil, getting the air to flow evenly through the soil in the chambers, adapting a heat gun as the heat source, designing everything to work at high temperatures (up to 200°C) and install temperature sensors in all the inlet airflows and chambers.

The final version, which was used for soil heating tests is shown in Figure 8.

Figure 8. Completed system during soil heating tests.

4.4. Soil heating tests

The final part of testing the proof of concept soil heating system, was to heat a range of soil samples to study how well the heating and cooling worked and also if weed seeds in the soil samples were killed.

4.4.1. Methods

Samples of soil from the BHU at Lincoln University were taken from Crowder tunnel one (43°38'59.70" S 172°27'21.71" E), Home Block North (43°38'59.36" S 172°27'21.41" E), and Balfour block (43°38'56.97" S 172°27'28.41" E.). Based on the large population of weeds that have grown in these areas in previous years, they were assumed to have large weed seed banks. The soils were passed through a 6.35 mm sieve, then air dried in a glasshouse, and finally divided into 100g samples that were stored in zip-lock plastic bags ready for treatment. Soils were collected in April 2017, while the final year project was in progress, but, with the delays, the soils were not treated until December 2018. The four samples for heat treatment and the four control (unheated) samples were randomly selected.

The soils were heated using the following sequence:

1. Spare soil samples (100 g) were put into the three chambers.
2. The system was run with the heater set at 300°C until all the temperature readings stabilised, to ensure the system was fully warmed up.
3. The soil samples were then advanced through the system starting from the bottom to the top, i.e., the bottom chamber was discharged to the collection vessel; the bottom chamber gate was closed, the middle chamber gate was opened so the soil in the middle chamber dropped to the bottom chamber, the middle chamber gate was closed, the top chamber gate opened to drop the top chamber soil into the middle chamber, and then the top chamber was filled with untreated soil. The progressive dropping the soils from one chamber to the next was done as quickly as possible.

4. The samples were held in each chambers for ten minutes so total time soil was in the system was 30 minutes.
5. Soil and air temperatures for each chamber were recorded at 0:00, 5:00 and 9:00 minutes.
6. After ten minutes, the dropping sequence, outlined in No 3. above, was repeated, to progressively move the samples through the heating system.
7. The three soil samples used to pre-heat the machine were discarded. Only soils that were treated when the machine was running at full temperature were kept for seed germination tests.
8. To ensure all soil samples for germination tests received identical full treatment, further spare samples were used to fill the top and middle chambers until the test soil had fully progressed through the system.

Soil samples for germination testing were returned to zip-lock backs and immediately taken to a heated greenhouse at Lincoln University for germinating.

Round, clear plastic, tubs, 110 mm diameter and 70 mm high, had four, 5 mm dia., equally spaced holes drilled in the bottom edge of the tub for water penetration and were then filled to 3 cm depth with medium grade vermiculite. A double layer circle of cheese cloth was placed on top of the vermiculite and soil samples were then placed on top of the cheese cloth, one soil sample per tub. All the tubs were then placed in a watering tray which was kept sufficiently full of water that all the tubs were kept moist. After 29 days, the number of seedlings were counted and removed, then watering was stopped and the tubs and soil allowed to dry out for 35 days, before being rewetted and a second count taken after 25 days post rewetting, followed by another watering cessation for 52 days followed by a final wetting for 39 days and the third and final count was taken. Counts for monocotyledon and dicotyledons were taken separately. Results were analysed with ANOVA.

4.4.2. Results and discussion

4.4.2.1. System heating temperatures

Across all the treated samples of soil, the average temperature, for each chamber and air supply, at the three measurement times, are presented in Table 4.

Table 4. Average temperature °C, for the six measurement locations and three measurement times.

Location	0 minutes	5 minutes	9 minutes
Top chamber	95	93	94
Top air	77	82	82
Middle chamber	83	104	108
Middle air	161	162	162
Bottom chamber	97	68	59
Bottom air	29	29	29

Most temperatures were relatively constant across all four measurement times, with the exceptions being the middle chamber which initially increased before leveling off, and the bottom chamber where the soil temperature decreased continually. The middle air value should be constant over time, as this air is exiting the thermostatically control heater system. The middle chamber soil would be expected to increase in temperature as it is being exposed to the hot air from the heat gun. An additional measurement of the air exiting the middle chamber would of been valuable. The temperature of the bottom chamber decreased as expected, but, the air entering the bottom chamber was constant, which was unexpected as this should of been warming up as its source, the top chamber, should also have been warming up. However, the top chamber also stayed nearly constant, while it should of been increasing (pre-warming), as should the top air that was transferring the heat from the cooling bottom chamber.

It therefore appears the heat transfer from the treated soil to the newly added soil was not working as well as planned. The likely cause is considered to be the difficulty in effectively insulating the system, particularly the fan cases, which were uninsulated aluminium, so they could well have been loosing a considerable amount of heat.

The key temperature, that of the soil in the middle chamber, was held at just below and then just above 100°C for the majority of the ten minute treatment time, which, based on the seed heating tests in part one (above) should of been sufficient time to kill most of the weed seeds in the soil. In addition, the soil in the top and bottom chambers were also at, or greater than, 70°C for part of the 10 minute cycling time, which is also sufficient temperature and duration to achieve some weed seed kill. Therefore the total treatment duration and temperature should be sufficient to kill all of the weed seeds in the treated soil.

4.4.2.2. Weed seed bank germination

The overall numbers of weeds germinating in the untreated controls were much less than expected considering the collection sites had been very weedy in the past. The cause of the poor germination is not known, but, it is believed that the 20 months the soil samples were stored in their 100 g sample bags, in the air conditioned laboratories, may have caused the seeds in the soil to loose viability. Due to the low numbers of emerging weeds all the counts for monocotyledons and dicotyledons were pooled for each counting date. For all three counting date there was no difference in emergence among the three soil collection sites ($p>0.05$) so the results for the three soils were also pooled (Table 5).

Table 5. Mean number of germinated weeds in the two treatments (heated, and unheated control) for each of the three counting dates and the overall mean.

Count	Heat treated	Untreated	p value	$LSD_{0.05}$
First	0.42	3.50	<0.001	1.088
Second	0.00	1.50	0.002	0.880
Third	0.33	1.25	0.029	0.809
Overall	0.75	6.25	<0.001	1.476

Despite the problems with the low total number of emerged weeds in the untreated controls, the results are unambiguous in that the heat treated soil produced highly significantly lower numbers of seedlings. It was unexpected that some weeds did still germinate in the treated soil. The hypothesis for this, is that the results in part one of this report showed that even 10 minutes treatment at 100°C can still result in a few seed surviving. This result, in combination with results of part one of this report, is taken as further evidence that temperatures higher than 100°C, e.g., 150°C to 300°C will be required for high seed mortality at short durations, e.g. < 30 seconds.

4.5. Conclusions

Despite the significant challenges in building the soil heating system, and, that the heating system is a proof of concept, not a working machine, the results are still considered valuable.

The main outcome is that the students have confirmed, via both thermodynamics and engineering, that the concept of recycling the heat / energy to increase the efficiency / decrease the energy / fuel used is viable, and, potentially high levels of heat recovery are possible. This is considered an important validation of the concepts proposed in Merfield (2013a).

In addition to confirming the physics and engineering, the proof of concept heating system, has been used to heat soil and kill the majority of the weed seeds. However, the results should not be over interpreted as the system is very simple compared to the vision of the final working system.

It would be possible to run further tests with the heating system, e.g., without the heat transfer from the bottom to top chambers, and compare that with the system running with heat transfer. However, as the heating system is 'very' proof of concept, with many areas for heat loss, so to get a more viable demonstration of the ability to recycle the heat would require a major upgrade of the insulation, which is not considered worthwhile. It considered better to develop a working prototype using a continual flow heat exchanger to maximise heat recovery.

It is concluded that the work undertaken by the final year project students Daniel, Jarrod, Joseph and Thomas, plus the summer scholarship student, Hamish, has been highly valuable in moving the potential of soil thermal weeding significantly forward and therefore much closer to a field prototype.

5. Overall conclusions

While both pieces of work produced valuable results, that have significantly progressed soil thermal weeding with heat recycling, they both also have limitations. Neither can therefore be considered to be full 'proof' of the concept.

The mustard seed heating experiment has clearly shown that the minimum temperature at which rapid (<30 seconds) weed seed mortality can be achieved in soil will be closer to 200°C than 100°C, and even potentially >200°C, but, the optimum temperature still needs to be determined. This needs to be done with soil containing real weed seeds if it is to fully inform the design parameters of a continual flow heat exchanger.

The effect of seed moisture levels on mortality was unexpected, but, on reflection, further work on the effect of moisture content on seed mortality and also the heating system needs further research.

The University of Canterbury project, has provided the confirmation that the thermodynamics of heat recycling presented in Merfield (2013a) are valid. However, while the proof of concept heating system is able to kill weed seed in soil, is some way from the vision for the final continual flow design, which, should also be able to achieve even higher levels of heat recovery. These outcomes therefore also need to be extended further with the creation of a laboratory scale heat exchanger with a design as close as possible to the vision for the field prototype machine.

The next steps are to undertake further tests using the retort system using weed seed containing soil to identify the rate of seed death at temperatures from 150°C to 300°C and also to study the effect of different soil moistures on heating and seed death at the optimum temperature.

From there the a larger-scale, laboratory based, continual flow, heating and heat recovery system needs to be designed and built to validate the engineering and also confirm its efficacy in killing seeds. From there it is hoped that a tractor mounted prototype can be constructed.

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Appendix
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26/10/17

Dr Charles Merfield
BHU Future Farming Centre
The BHU
Corner of Weedons and Farm Road
Lincoln University
Canterbury
New Zealand

Dear Dr Merfield,

Final Report: Soil Thermal Weeding

The Soil Thermal Weeding team is submitting the attached final-year report for your consideration. The focus of the report is to review the solution, along with all required information to implement it. We have organised a time to demonstrate the device and explain any hazards that are present.

This report includes project achievements, schedule, budget, health & safety risks, implications, future issues & limitations, and our contribution statements.

We hope that this report meets your requirements and we thank you along with the BHU Future Farming Centre for supporting this project with funding from AGMARDT.

Regards,
Daniel Smithies, Jarrod Tucker, Joseph Towers and Thomas McRobie

Department of Mechanical Engineering

ENME 408 Final Year Projects

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Final Report
Soil Thermal Weeding
M03

26 October 2017

Daniel Smithies
Jarrod Tucker
Joseph Towers
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BHU Future Farming Centre

AGMARDT

Executive Summary

The purpose of this project was to develop, to the ‘proof of concept’ stage, a more energy efficient method of killing emergable weed seeds in soil, for vegetable growers and arable crop farmers. This project was supported by Dr Charles Merfield at the BHU Future Farming Centre with funding from AGMARDT.

This report details the work which was completed by the team. The project began with research into existing methods of thermal weeding and alternative means of seed sterilization. A number of concepts were generated, with the ’vertical sections’ concept chosen for development after theoretical simulations and experimental testing. The prototype device that was constructed utilises convection as the means of heat transfer, using air as the transfer medium. Separate air streams allow for heat recycling pre-heating and cooling the sections of soil either side of the central heated section.

Results gathered from testing of the prototype device show promise in the heat recycling, however do not meet all requirements that the team set out to achieve. Ultimately, more powerful blowers are needed to reach the target values for output volume and temperature.

The spending to date for the project is $1,758. This is more than initially anticipated in the proposal, but does not go past the $1,000 contingency, and is well below the $7,500 budget available for the project.

Contents

Chapter 1

Introduction

Non-chemical methods of weed control are of considerable interest, particularly, but not limited, to the growing organic foods movement. Open flame and electrocution methods are used to kill emerged weeds prior to crop planting, and to control emerging weeds between crop rows during crop growth. These methods are energy intensive and cannot manage weed growth within the crop row during the growth period.

Figure 1.1: Swedish band steamer using steam injection without mechanical mixing using 600 kW steam boiler water tanks and associated equipment. Photo credits: Bo Melander.

A more effective method is to kill the bank of seeds in the soil, before they germinate and emerge. This only needs to be performed on the top 5 cm of soil, as seeds deeper than this cannot reach the surface before running out of energy. This treatment provides total emergable weed prevention, conceivably, for the entirety of the growth season of the crop. The treatment will not be so effective against creeping weeds, such as Californian thistles, other treatments will have to be considered in conjunction.

This project is interested in developing to the 'proof of concept' stage, a more energy efficient method of killing the emergable seed bank in agricultural soils. This not only has application to high value crop farming, but, if cost effective enough, could be employed to all aspects of agriculture, or even when soil needs to be transplanted from site to site, where cross-contamination of seeds is an issue, such as for civil construction purposes and for domestic gardens.

1.1 Scope Changes

There have been no scope changes since the mid-year report.

Chapter 2

Achievements

2.1 Research

The team considered different methods of killing weed seeds in soil. Microwave irradiation seemed a likely candidate initially, but was quickly discarded as seeds are indistinguishable to soil for microwaves (See Appendix A.1).

60 °C is a sufficient internal temperature to cause biological damage in seeds. Increasing the temperature will increase the rate at which damage is inflicted. The client has performed research on this subject, the results of which can be seen in Appendix B.2. From these findings, a time at temperature of 15 seconds at 200 °C was set as a goal for the prototype unit.

Methods of treating bulk solids, such as grain or milk powder were investigated. These methods have similarities to what the project is hoping to achieve, with soil being similar to a powder. They use parallel 'pillow' plates which have a fluid flowing within them, to heat a gravity-fed bulk solid. Below the hot plates are cold plates which are used to cool the bulk solid and recycle the heat.

The team determined to explore concepts where the entire soil and seed mixture was heated to lethal temperatures, and then the heat was recycled and used to preheat the incoming soil. A summary of the thermodynamic relations is included in Appendix A.2. Such a scheme will reduce the total energy cost of heat based seed killing.

2.2 Concept

The team considered multiple concepts to heat soil to 200 °C and then recycle the heat in order to improve efficiency. The team arrived at three main concepts that were deemed promising.

The first concept utilised conduction to heat the soil, and dropped soil through the system using gravity. See Appendix C.1 for details. This concept was rejected as theoretical predictions of heat transfer (see §2.3) showed that convection was much faster than conduction in soil.

The second concept used discrete 'buckets' to heat batches of soil by blowing a hot air-stream through the soil. The heat was then recycled by cycling air through the hot batch, and into the next batch. For this to work there would need to be a method of changing the air-streams around, or shifting soil between buckets, which would significantly add to the complexity of the design. See Appendix C.2 for details.

The chosen concept utilises the best aspects of the previous concepts. As shown in Figure 2.1 the soil enters in the top of the device which is gravity fed through to the exit at the bottom. The soil in the middle section is heated to the target temperature of 200 °C by a circulating airflow with the external heat source. Once the soil has been heated it is dropped to the lower section by opening the separating shutter (or gate). Here a separate airflow cycles the heat from the bottom section to the top. This preheats the upper section and cools the bottom section of soil.

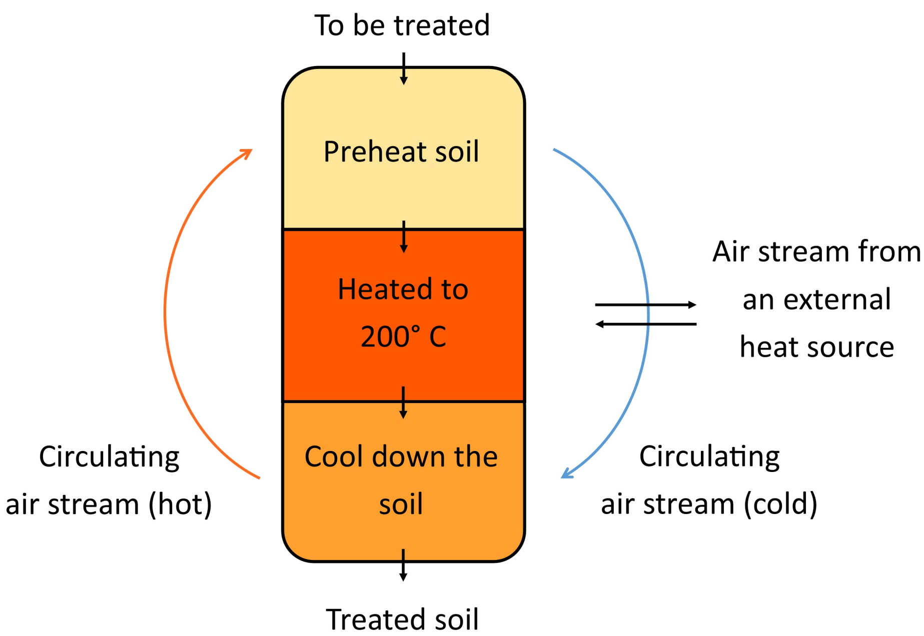

Figure 2.1: Sketch of the Vertical Sections Concept. The red and blue arrows indicate the circulation of hot and cold air between the different sections, the horizontal arrows show the heat circulating between the heat source and middle section, the vertical arrows show the direction of soil flow.

The performance of the design can be improved by increasing the number of recycling sections. Table 2.1 summarises the theoretical performance as the number of sections is increased. These results assume that the batches of soil in the recycling sections come to complete thermalisation, and that no heat is lost through the walls of the device (see Appendix A.2 for calculations).

Table 2.1: Heat recycled vs. number of sections assuming each section thermalise completely.

Number of Sections	3	5	7	9	11	13
% Heat Recovered	50	67	75	80	83	86

2.3 Development

The team carried out further development with two concepts; 'vertical sections' and 'parallel plates'. The key difference between the two concepts was the method of heat transfer into the soil. The first concept only utilises conduction from hot plates, while the second uses convection of hot air with conduction as a lesser effect.

The team employed 2D numerical heat transfer simulations using both Matlab and Comsol to determine the most effective method of heat transfer (see Appendix D). The results showed that convective heat transfer was more effective than conduction alone, as expected, favouring the 'vertical sections' concept.

The 'vertical sections' concept involved passing air through soil, thus the team needed an idea of the pressure required to push air through a specific amount of soil. Darcy's law was used in conjunction with the Kozeny-Carman relationship to attain an approximate value for pressure requirement per unit length (see Appendix D.2.1). The estimates show that the pressure required is on the order of 100 Pa/m, however, this depends on the properties of the soil which can be highly variable. It also assumes that the soil particles are regular sized and shaped, which is definitely not correct. Despite this, the Kozeny-Carman approximation is the best theoretical result that can be achieved in the absence of experimental results.

2.4 Experimentation

2.4.1 Temperature and Pressure Tests

A basic heat gun was purchased for testing the heating characteristics of soil. The mostly plastic XU1 heat gun was rated for 2 kW and had 2 heating settings. The heat gun was fixed to a chamber of soil and ran with the inbuilt fan to blow heated air through soil. The blower on the heat gun had insufficient pressure head to force air through the soil, and so began to overheat.

A camp bed blower was then purchased to augment the pressure of the heat gun blower. This was secured to the inlet of the heat gun, working in series. The camp bed blower had more than enough pressure to move the heated air through the soil. The soil temperature was measured to be between 80 to 160 °C after heating for 1 to 2 minutes. This was measured using an infra-red temperature sensor.

2.4.2 Airflow Tests

The previous tests showed that the soil can reach the desired temperatures, and that air can be blown through the soil. The question then was whether the soil can be heated evenly with all the material reaching the required temperature. The team found that the air stream would force a singular pathway through the soil, and then only heat the soil closest to the air stream. To resolve this the team trialled mechanical mixing, shaking and different section shapes.

Mechanical mixing was trialled using a stirrer to mix the soil in a square section. This showed positive results as there was a more even temperature distribution throughout the soil. However, the corners of the section were inaccessible, and the stirrer is an additional moving part exposed to the abrasive soil.

A shaking test rig was constructed using an off-set motor and a singular section. The shaking collapsed air channels in the soil as they formed, causing the air to more evenly flow through the soil. The disadvantage of this method is that it would drastically reduce the life time of the device through fatigue, especially on the seals.

The final test was to see if changing the section shape and size would change the flow behaviour. The most effective section shape was a rectangular 80 x 40 mm where the inlet air is along the wider side. This is effective as the air stream blown through the soil is approximately in the middle, and an 80 mm width is appropriate for the pressure of our testing blower.

The team decided that changing the section size and shape was sufficient to achieve even heating, and so the mechanical mixing and shaking concepts were abandoned.

2.5 Prototype Device

The main structure of the prototype device is constructed from $80 \times 50 \times 3$ mm Aluminium RHS. This RHS is split into four sections, bolted together using angle iron flanges. A photo of the prototype device is shown in Figure 2.2.

There are soil gates in the middle of the each of the 4 sections, which separate the column into the 3 airflow sections. The top and bottom sections are the preheating and cooling sections, with the hot air stream being circulated through the middle section.

Airflow inlets and outlets are integrated into the gate assemblies, which allow connection to the high temperature silicone ducting. High temperature gas blowers are used to move the air in the different air streams. In the middle air stream section, air passes through the heating element of a 2 kW heat gun before entering the soil to heat it.

The device as a whole is sealed, using a high temperature resistant silicone sealant to stop air from escaping. Insulation covers the device to reduce the heat loss, improving the time taken for the soil to reach temperature.

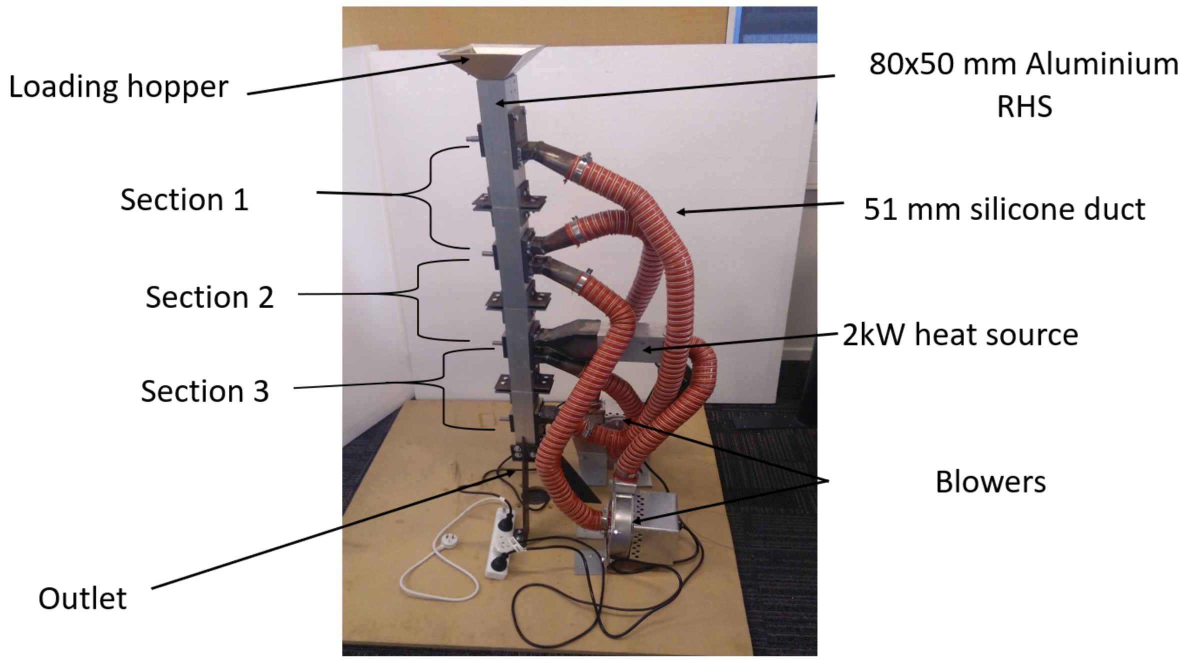

Figure 2.2: Prototype device before insulation was installed.

2.5.1 Sections and Joints

The profile of the sections was selected so that the air-stream would flow through most of the soil as it flows from the inlet to the outlet. The section length was selected as it allowed the bulk of the loose soil, that got picked up in the air-stream, to drop out, before the air-stream exited through the outlet. This will reduce the amount of fine soil travelling through the hot air gun and blowers.

Aluminium was used as it was the most convenient to source and work with, and it reduced the weight of the device compared to steel. However, this led to further complications, as it could not be easily welded to, and although it could be drilled and tapped, the threads are easily stripped if over tightened.

The sections were connected together by making flanges out of 30mm angle iron. These were bolted to the side of the Al sections, then the sections were bolted together via the flanges. This proved to be a sufficient design, as it allowed the team to de-construct and work on different sections independently, and allowing access to the gate mechanisms in each section.

2.5.2 Gates

The purpose of the gates was to hold the soil in the separate sections. They needed to be able to drop the soil from section to section, and stop air from flowing between sections or out of the Al section.

The gate assemblies were made up of four main components; the inlet/outlet plate, the turning shaft, the turning flap and the handle plate. The gates were fixed to the Al sections using bolts into threaded holes in the sections, and the plates sealed with high temperature silicone gasket sealant. The turning shafts were sealed using high temperature O-rings, which allowed rotation while stopping air and soil from escaping.

The inlet/outlet and handle plates were made from carbon steel, using a mill to drill holes for fastening to the Al section and cut out the inlet and outlet slots. The turning shaft was also made from carbon steel, turned down to size in a lathe, and then O-ring grooves cut. A flat was milled in the shaft, then two holes were drilled and tapped to allow connection of the turning flap. The turning flaps were made from an aluminium strip, cut to approximate size and then drilled to match the holes in the turning shaft. The sides of the flaps were then gradually filed down to fit tightly within the Al section, providing a reasonable air seal between sections.

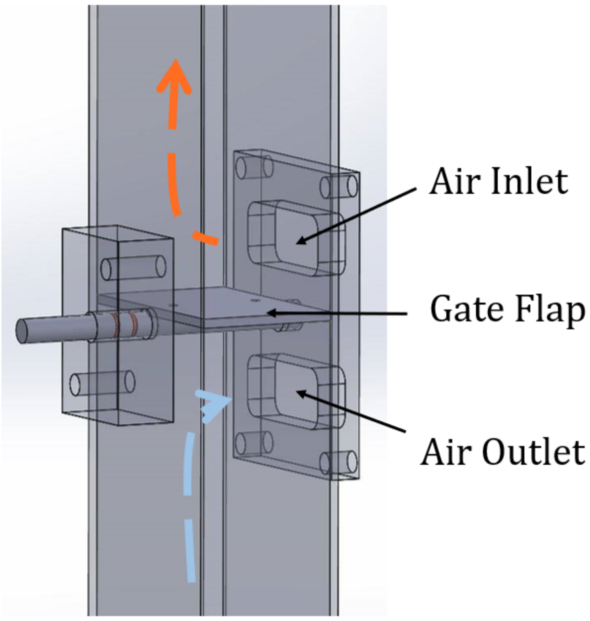

Figure 2.3: CAD drawing of gate assembly.

2.5.3 Pipes

The team had the option of utilising hard metal pipes or a more flexible air duct material. The metal pipe option would have been better for reducing the resistance to airflow, however, assembly and reconfiguring of the pipes would have been more difficult. This was seen as the most pressing concern in the prototype phase of the project.

51 mm Silicon duct was utilised instead. This was a more expensive option than hard pipe, at over $120 per metre, but it is one of the few flexible materials that can withstand the >200 °C that is required. The grade of silicone duct used is rated up to 360 °C, more than sufficient for the purpose.

2.5.4 Heat Source

The team utilised a 2000 W Bosch air gun to provide the heat to the middle section of the prototype. The plastic housing heat gun can provide between 50 - 630 °C. Due to the low heat transference rate from the air-stream to the soil, it was decided to cycle the heat from the outlet of the soil section, back through the hot air gun. Thus, minimising heat loss and a decreasing heating time.

The heat gun in its original configuration was not appropriate for this task. It is designed to take in cold air, via a plastic blower fan and some low temperature electronics, before entering the heating element. The team commissioned the electrical technician to separate the heating element from the temperature sensitive components. The heating element was placed in its own metal enclosure, constructed from a 80 × 80 mm Al SHS. The electrical wires inside the enclosure were upgraded to a fibre wire which can withstand 400 °C and the safety heat fuse upgraded to a Non-Resettable Thermal Fuse rated for above 240 °C.

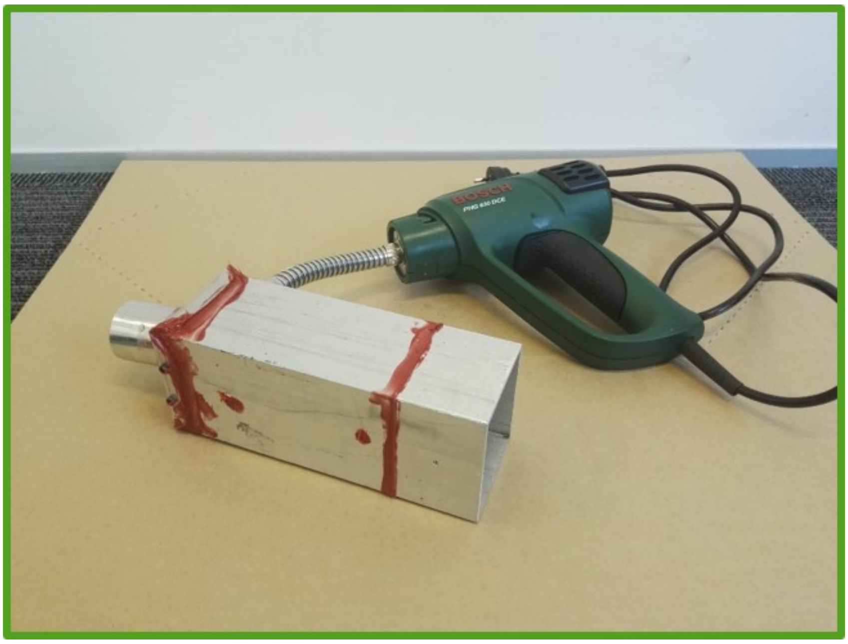

Figure 2.4: Adapted Bosch heat gun with the heating element and plastic housing separated.

The main electrical board along with its various components were left in the plastic housing with the on/off controller. This is attached to the heating element via a metal wire casing. This heat source has been approved by a trained electrical technician.

2.5.5 Blowers

The team formulated the requirements for the blowers from theoretical calculations and some limited testing with a camp bed blower. It was decided that 15 m^3/hr and > 100 Pa airflow was required. The main limitation was the intention to pass hot air at > 200°C through the blowers. This meant that the impeller of the blower must be of metal construction, and that the drive motor was independently cooled.

The team searched suppliers locally and on the internet for suitable blowers. There are many applications where blowers are used in industry, such as for grain drying or powder transport. However, blowers for small scale applications, such as this project's bench-top device, are limited. The team decided to take a chance on a blower that could be obtained from a New Zealand supplier. The specification sheet was incomplete, but this was not unusual for the smaller blowers available. Unfortunately, the stall head of the blowers is lower than desired. The blower is only able to push air through 2 to 3 cm of soil, where the team desired > 5 cm.

The blower used on the prototype is shown in Figure 2.6. The motor and wires were exposed, and so required a safety cover to be constructed that prevented the user from harm, while not blocking the cooling of the motor. Also, the intake and outlet of the blower needed to be adapted to the 51 mm circular pipes. This was achieved with aluminium sheet, rivets, and silicone gasket to seal the gaps.

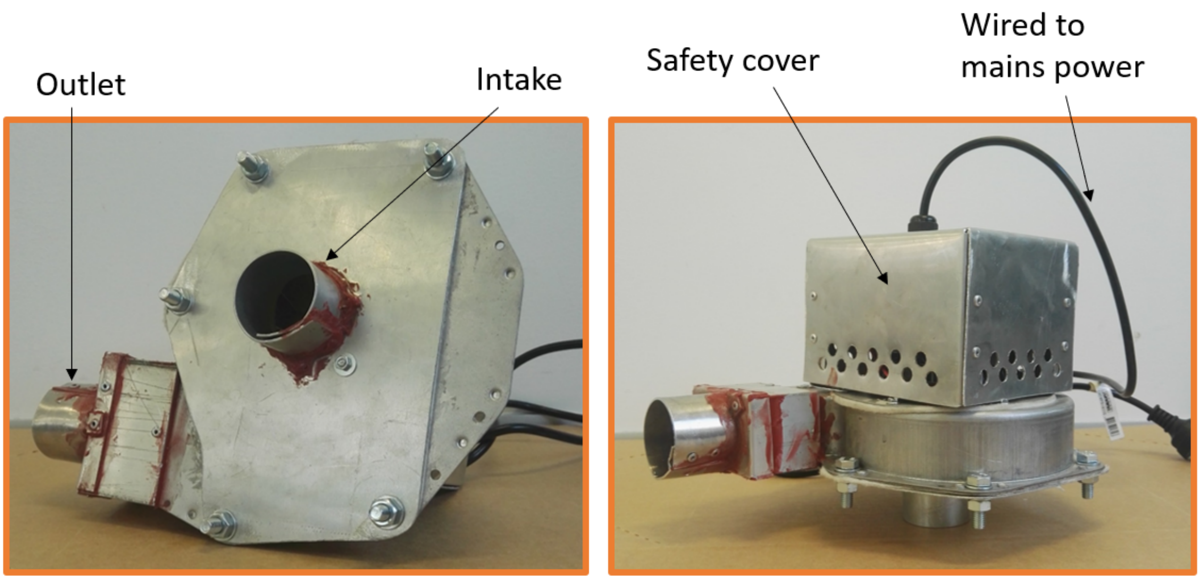

Figure 2.5: Hot gas blower used on the prototype device.

2.5.6 Temperature Measurement

The temperature of the soil and air-stream in each section can be measured using the six thermocouples connected to an arduino based LCD display. This allows the user to read the temperature off the display, and can then cycle the soil through once the batches are at sufficient temperature.

Table 2.2: LCD screen readings

	Left	Middle	Right
Top row	Middle section air in	Top section air in	Bottom section air in
Bottom row	Middle section soil	Top section soil	Bottom section soil

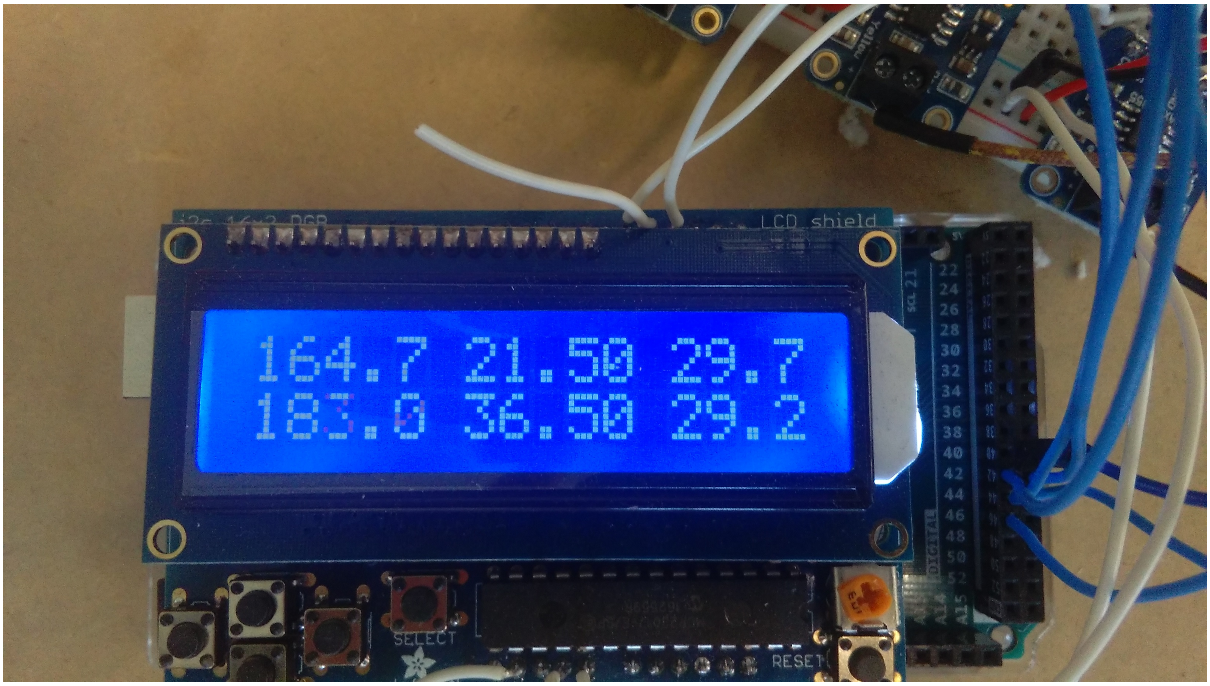

Figure 2.6: LCD screen for displaying temperatures

2.6 Results

2.6.1 Soil Volume

The pressure provided by the blowers is a constant that cannot be easily changed. Therefore, the first step was to determine the appropriate amount of soil that the blowers could push the air through. This was lower than desired, with the airflow getting blocked if more than 200 ml of soil was put in. We observed that this could be increased to 250 ml if the blowers were running when the soil was dropped into the section. This allowed the momentum of the air to keep flow going.

2.6.2 Heating

The device was first preheated without any soil in it to heat up the steel components that have a relatively high thermal storage. The insulation performed well on the device with all surfaces not exceeding 30 °C, safe for bare skin to touch for extended periods.

After preheating, soil was placed in the middle (heating) section and the temperature was measured at regular time intervals. This was performed several times (see Appendix

E for data). The average result can be seen in Figure 2.7 where the blue curve shows the temperature over time of the soil without heat recycling.

The red curve in Figure 2.7 shows the temperature vs. time of the middle (heating) section of soil when the recycling sections are used to preheat the soil. By doing the temperature recycling the soil started approximately 30 °C higher meaning that less time, and therefore less energy, was used to heat the soil.

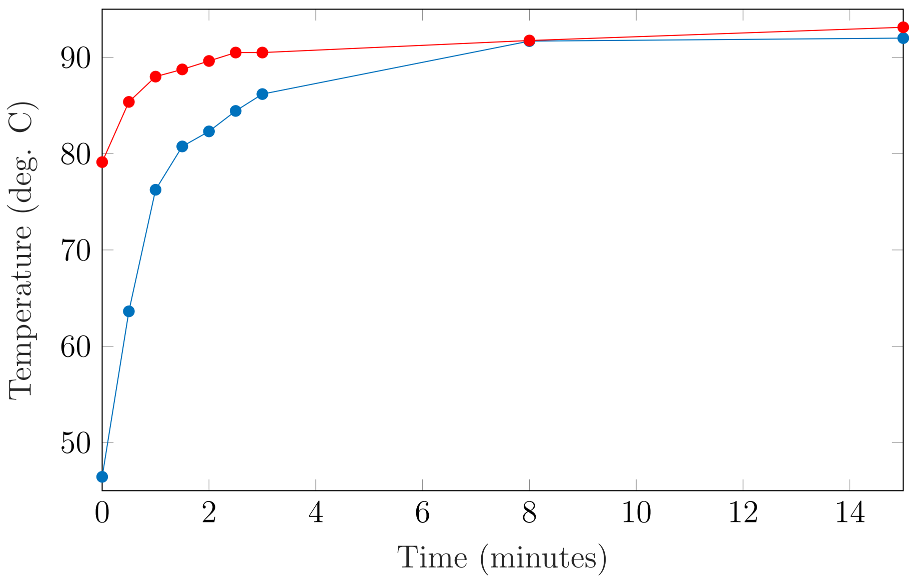

Figure 2.7: Temperature over time of soil in the middle section of the prototype. (red line): with heat recycling. (blue line): without heat recycling.

These results could also have been caused by conduction between the middle section and the top section, causing the heat source to work harder to heat both the middle and top section, instead of from heat recovery. Further tests will be required to eliminate this possibility.

The temperature measurements from when the temperature was not being recycled can be found in the Appendix E in Table E.1. The measurements with the heat recycling can be found in Table E.2 and E.3.

Chapter 3

Project Management

3.1 Gantt chart changes since proposal

The original project plan outlined the initial research, concept development, prototype build and then the final testing. The plan showed that 22 days of research was to be completed along with 28 days of concept development and 88 days for the prototype construction. Since then, the Gantt chart has developed and improved as the achievements were completed.

One of the major schedule changes was the removal of the "produce CAD drawings" as the team found that it was unnecessary, would save time and the design may change in the near future. As a solution we only professionally drew the most complex parts (i.e. gate assembly) and the parts that were to be manufactured by a technician.

The final Gantt chart shows more detail, containing subtasks and parallel work streams. The parallel work streams were initiated for the research and simulations, airflow testing and the build. Overall, the final project plan has been derived of the original, containing more detail and the exact timing.

3.2 Budget

The budget that the team provided in the project proposal, in March 2017, is shown in Table 3.1. The actual chargeable costs at the end of the project, October 2017, are shown in Table 3.2. The budget from the proposal was lacking detail as the project was in the conceptual stage at the time. This meant that the team estimated the cost of the build without knowing the full solution. Even so, the final cost of the build was less than the contingency allowed for in the proposal. Furthermore, the sponsor later informed the team that the budget available for the project was $7,500, and so the final cost of the project was well below this limit.

Table 3.1: Initial budget from project proposal in March 2017. Figures in New Zealand Dollars.

Item	**Quantity**	**Description**	**Cost**
Prototype Unit Build	1	Parts and materials for building 'proof-of-concept' unit	\$1,000
Seed and Soil Types	1	Testing material	\$100
Site visit(s) (Conditional, subject to project's needs)	1	Observe and obtain close-up information *in situ*	\$200
Contingency	1	Any unaccounted fees	\$1,000
Total			**\$2,300**

Table 3.2: Chargeable costs of the project at the end of the project, October 2017. Figures in New Zealand Dollars.

Item	**Description**	**Cost Per Unit**	**Quantity**	**Cost**
Hot air gun	Bosch variable temperature heat gun used for heat source	\$112.17	1	\$112.17
Thermocouple amplifier	For temperature measurement	\$64.14	6	\$384.81
Electronics	For displaying temperature measurements	\$143.61	1	\$143.61
Hot air blower	2500 RPM metal impeller centrifugal air blower	\$175.50	2	\$351.00
Thermal fuses	Installed in hot air gun	\$9.23	1	\$9.23
51 mm Silicon duct	Flexible high temperature ducting	\$134.50	4 m	\$537.98
Mineral wool insulation	25 mm thick, suitable for 200 to 300 °C heat range	\$161.00	1 roll	\$161.00
Miscellaneous testing equipment	Camp bed blower, DC motor, basic hot air gun, etc.	..	..	\$58.22
Total				**\$1,758.02**

3.3 Health & Safety Risks

The table below covers the health and safety risks of building and operating the prototype unit (5=certain,1=almost never):

Table 3.3: Health and safety risks to the user of the prototype

Risk	Likelihood	Severity	Mitigation
Hot parts	4	3	Guards, insulation, training for users, closed system, cooling of matter exiting unit, PPE, use in open space.
Rotating/Vibrating Parts	4	3	Guards, closed unit, training, PPE.
Injury while lifting	4	2	Safe lifting practises, store and run unit on ground/sturdy setting.
Electrocution	2	5	Insulation/shielding of electrical components and wiring, appropriate grounds.
Insulation (fibre dust)	5	4	Gloves and dust mask when adjusting.
Soil (dust inhalation)	4	4	Use device in open spaces, dust mask.

3.4 Implications

3.4.1 Work Incomplete

The blowers that were installed on the prototype were insufficient to achieve the desired performance. The blowers were designed to push air with little to no head, and were unable to force air through more than 2 cm of soil. These blowers will need to be upgraded.

The team has sought advice and searched, but has yet to find a suitable alternative. There are blowers available which have enough head, however these are designed for larger industrial applications and are physically too large to fit into the prototype. One possibility is to re-purpose an automotive turbo, however, this will require driving it at 10 to 20 thousand RPM, and there are no off-the-shelf units available.

3.4.2 Further Improvements to the Prototype

By improving the blowers a greater stall pressure will be produced and higher overall pressure. This is needed for a consistent and evenly distributed air flow through the soil. Ideally this would help with even heat transfer and natural mixing within the soil sections. This will also allow the device to treat larger volumes of soil and therefore, quicker feed rate.

Improved blowers will also improve the air flow around the heating element of the hot air gun, which would stop it from cutting out from overheating. This means that there would be a constant 2 kW of heat being added to the air stream. If this is still not enough heat, a second hot air gun may need to be added or the heat source may need to be changed to an LPG burner.

3.4.3 Commercial Device

The prototype device is solely to serve as a proof of concept, thus limited to testing with only small quantities of soil. There are a number of aspects which would need to be researched in order to build a commercially usable device.

A larger version of the device would need a much higher pressure blower, so scoping would be required to get the correct blowers for the column size and the amount of soil being processed. Due to the larger size a diffusion device for the air entering the soil would become much more important to ensure consistency of the air flow. A commercial device could become very tall, especially if more sections are added, this could prove to be an issue in terms of loading the untreated soil; possibly an angled or horizontal system could somehow be used.

The electric hot air gun would obviously not provide enough heat to the soil in a larger version. An alternative heating system would therefore need to be researched and implemented. This would most likely involve an LPG burner, which may involve a heat exchanger to transfer the heat into the air stream or passing the heat directly through the middle heated section without recirculating, whichever was more efficient. See Appendix D.4 for burner requirement calculations.

3.5 Ethical Issues

The team perceives no ethical issues to the prototype or the wide-scale implementation of the concept in society. Background research identified the destruction of soil microbiology as a concern, however, this problem is localised and strategies exist to limit the effects.

The only other ethical issue that the team can see is the fuel source for providing heat to the system. Fossil fuels are likely the most cost effective source, which has many wider environmental concerns. Also, care must be taken that toxins from burning the fossil fuels do not enter the soil that is then used for food production.

3.6 Conclusion

The team has performed research and generated concepts to solve the issue of weed control via thermal seed killing in soil. Three main concepts were identified as viable, and theoretical evidence was produced to support this. Simulations and hand calculations show that the most viable concept is through convection of a hot gas through the porous soil.

The team attempted to build a benchtop device to demonstrate the viability of the concept. This involved solving many smaller issues to do with the highly variable properties of soil, such as porosity and abrasiveness. For the most part the team was successful. However, the team was not able to achieve the temperature and processing rate target identified in the proposal.

The benchtop prototype device requires further development in order to achieve the original goals. Better hot air blowers should allow all targets to be met. Despite this, the initial heat test results are promising. The results showed a reduction of the time required to heat the batch of soil of around 50%, although, this does not take into account the leakage of heat between sections. Further testing is required.

3.7 Contribution Statements

3.7.1 Joseph Towers

My task in the research phase was to investigate the viability of using microwave irradiation for seed killing in soil. I contributed to the group effort of concept generation but was most involved with the concepts that used convection.

In the theory development stage of the project I was tasked with researching and simulating convective heat transfer in porous media.

I was involved with most aspects of the prototype build, my personal tasks were getting the blowers into a usable state by making motor covers and adapting the inlets. I also performed much of the machining for the gate assemblies.

3.7.2 Daniel Smithies

I cut out the aluminium for the central section, mounted the angle brackets to it and then bolted them together. I also cut out, welded and then bolted the stand to the MDF base, that I found, and the central section. I also acquired and cut out the meshes for the gates to hold the soil in. I bent and riveted the sheet metal for one of the blowers so that the pipes could fit onto it as well as making the stands for both of the blowers. The task of acquiring, soldering, setting up and programming the temperature sensors was also done by me. finally I also helped mill out the rectangular holed in the gate mounts and install the insulation on the device.

I worked on the burner calculations to find the air-to-fuel temperature ratios for the burner, the numerical heat exchanger calculations, 1D transient conduction of heat through soil calculations that later helped to back up by Tom and Jarrod's calculations of the same thing, 2D stepped conduction graph (Figure D.2) showing the temperature distribution with stepped plate temperatures, stepped plate heat flow into soil (in appendix), and a rough temporary plate prototype with a plate separation of 20 mm to see how soil would clump in the plate heat exchanger concept.

3.7.3 Jarrod Tucker

Initially I researched microwaves as an option to isolate and heat the emergable weed seeds. Existing articles and reports were investigated which led to similar uses of microwaves on seeds and various plants. Research into grain drying was also carried out due the similarities to our project and the methods that grain drying [6] uses, applications and scalability. Some sourcing of parts was achieved such as air-to-air heat exchangers, insulation, burners, heat sources, silicon ducting and electrical components.

Comsol models was formed to simulate the conduction through soil from a hot plate. This was a one-dimensional model using soil properties found from prior research.

Different insulation materials were considered for the device to ensure minimal heat loss and for a safe temperature for the exposed surfaces. Appropriate temperatures to touch metallic surfaces were found and then applied to find an appropriate thickness. I researched and organised the heat gun adaptation to allow for heat circulation. The heating element was also built along with the connection from the element to the middle soil section.

3.7.4 Thomas McRobie

In the research stages of the project, I was tasked with investigating alternative seed killing methods. This involved considering other methods such as chemicals and microwaves, however it was concluded that using solely heat was the best in our case as it works for all types of seeds and all seeds have a temperature at which they die.

During the development stages my tasks were to investigate the times required to heat soil to the required temperature. This involved hand calculations, simple Matlab scripts and COMSOL simulations, to compare the effectiveness of conduction and convection heat transfer to soil.

In the building stages of the prototype, my work streams were the gate assemblies and the gate the hose connections. This involved developing a design for the gates, sourcing parts and workshop time with technician assistance to get the parts made. As well as this I contributed to others sections of the build, when held up on my own. I also presented a range of blowers to the team, from which one was selected, as a team.

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Appendix A

Research

A.1 Seed Killing via Microwave Radiation

One of the original ideas initiated by the sponsor was to use microwaves to selectively heat the seeds and eliminate germination. The thought was that certain frequencies of microwaves would heat the seeds a lot more than the soil, which would require a fraction of the energy required to heat the entire system. Some research was done into microwaves and the molecules they affect as well as similar applications and it soon became obvious that this wasn't an appropriate solution [3, 4].

Microwaves are electromagnetic waves in the 300 MHz to 300 GHz range which couple very well to the H-O bond of water molecules. As these water molecules get increasingly agitated they begin to vibrate at the atomic level and generate heat. This is a quicker and more effective method compared to normal heating as the microwaves penetrate quite far into normal materials and so can heat from the inside.

Unfortunately, soil tends to have similar moisture content to the seeds, and the molecules in seeds do not appear to be any more absorbent to microwaves than the surrounding soil, so can't be targeted over the soil. Higher frequency waves could be a candidate for this purpose, but requires a lot more technical knowledge and are hazardous to biological tissue which could be a safety risk in industrial applications.

A.2 Energy Recycling

If a volume of soil, V, with specific heat capacity C and density ρ is heated from T_i to T_f, then the heat input required will be $Q = V\rho C\Delta T$. If a fraction ϵ of that heat was recycled from previously heated soil, then the heat input required is $Q = (1-\epsilon)V\rho C\Delta T$.

With a heat source that can supply the system with power P, this means we are able to process soil at a rate of

$$\dot{V} = \frac{P}{(1-\epsilon)\rho C \Delta T} \tag{A.1}$$

If the heat source were a heat gun that can supply 2 kW of heat in a 600 °C air stream, and we aim for $\epsilon = 75\%$ heat recycling, then we should be able to process approximately $\dot{V} = 56$ l/hr of standard soil. This number is highly dependent on the moisture content and type of soil and so could vary by up to a factor of 2.

Appendix B

Properties

B.1 Soil Properties

Soil Type	Water Content (%)	Bulk Density (Mg/m^3)	Dry Density (Mg/m^3)	Thermal Conductivity (W/m K)	Specific Heat Capacity (J/kg K)
BH C13 88	21.3	1920	1583	2.89	1520
China CLAY (D)(sat.)	46.2	1730	1183	1.52	2362
China CLAY (D)(dry)	0	1390	1390	0.25	800
Sandy CLAY	26.5	1890	1494	1.61	1696
Sandy CLAY	19.5	2100	1757	2.45	1459
Soft dark grey sandy gravely CLAY	28.5	1912	1488	3.57	1764
Soft grey fine sandy CLAY	54.6	1650	1067	4.20	2646
Soft grey fine sandy CLAY	41.4	1741	1231	3.03	2200
Stiff dark grey sandy gravely CLAY	10.1	2299	2088	3.69	1141
Stiff dark grey sandy gravelly CLAY	9.6	2369	2161	3.28	1125
Stiff grey brown sandy gravelly CLAY	9	2352	2158	3.20	1104
Very soft grey fine sandy CLAY	46.2	1711	1170	3.51	2362
Grey slightly silty sandy GRAVEL	11.1	1983	1785	4.44	1175
Grout	166	1250	470	0.64	6412
Grey limestone (very hard)	0.1	2690	2687	2.54	803
Course SAND (dry)	0	1800	1800	0.25	800
Course SAND (sat.)	20.2	2080	1730	3.72	1483
Dark grey clayey fine sand/silt	28	1848	1444	4.26	1747
Fine SAND (dry)	0	1600	1600	0.15	800
Fine SAND (sat.)	24.6	2010	1613	2.75	1632
Made ground (Silty gravely sand)	13.9	2182	1916	5.03	1270
Medium SAND (dry)	0	1700	1700	0.27	800
Medium SAND (sat.)	20.2	2080	1730	3.34	1483

B.2 Effect of Time and Temperature on Seed Germination

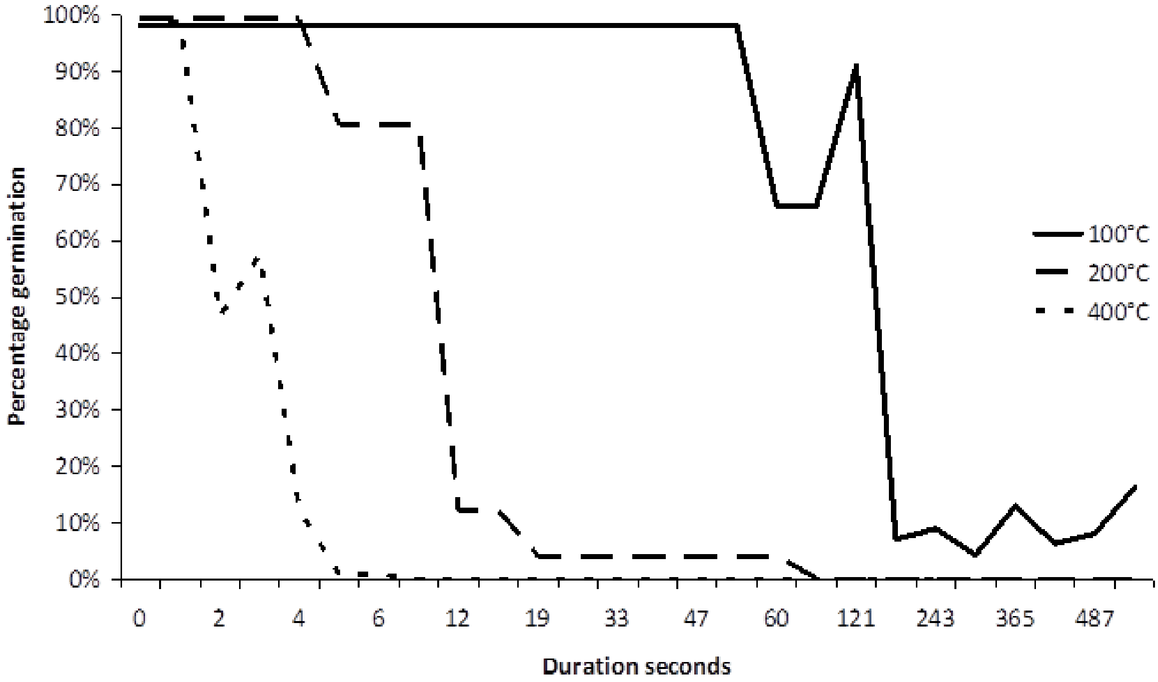


Figure B.1: Seed germination rate as a function of time spent at a few different temperatures. Data courtesy of Charles Merfield.

Appendix C

Concepts

C.1 Parallel Heating Plates

The first concept generated was the 'parallel plates' idea. Figure C.1 shows this design. The idea came about after researching existing products and finding how bulk solids are treated with heat.

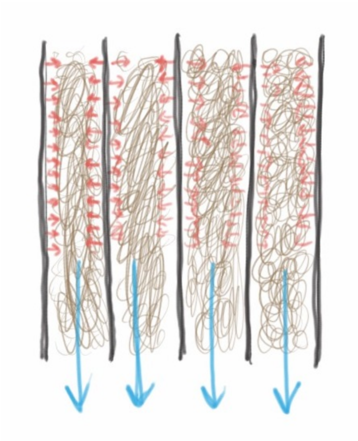


Figure C.1: Sketch of the Parallel Plate Concept. Blue arrows indicate the direction of the flow of soil and the small red arrows represent the heat transfer from the plates to the column of soil.

The method of heat transfer with the soil in this case is mostly conduction. The soil is gravity fed through the plates, with the flow rate being controlled at the bottom by either an auger or an appropriate valve. The plates would be hollow containing a coil within them to carry the heating fuel. This can heat the soil and then absorb heat back from the soil in the lower part to be recycled.

C.2 Buckets

Another concept generated was the 'buckets' idea, as shown by Figure C.2. This concept uses convection rather than conduction as the method of heat transfer with the soil. This readily leads to heat recycling as an air stream through the soil can be used to cool the hot soil and preheat the incoming soil.

The idea is that the middle bucket of soil is initially heated up to 200 °C and then shifted right a spot. This heated bucket of soil is then linked to a bucket at room temperature and air is circulated between them (2 and 4). The air circulating between the buckets will move heat from the hotter bucket to the colder one. They will balance at a temperature of 110 °C, assuming complete thermalisation, before the buckets are shifted right a spot. The bucket now in the middle spot will be preheated and take less time to heat to 200 °C.

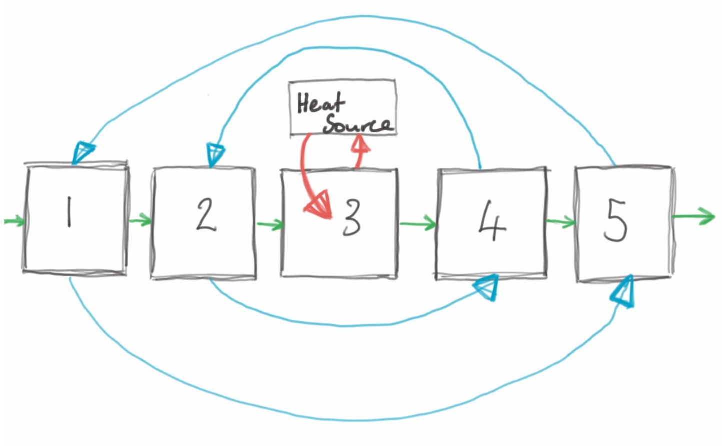


Figure C.2: Sketch of the Buckets Concept. The blue arrows indicate the circulation of air between buckets, the red arrows represent the heat input into the centre bucket, and the green arrows show the direction that the buckets of soil will move along.

The number of buckets can be varied depending on the amount of heat recycling that is required or how simple the build needs to be. The heat recycling obtained as the number of buckets is increased is shown in Table 2.1. This data assumes that each pair of buckets reaches complete thermalisation before moving along. If instead only 90 % thermalisation is assumed, then the recycling will be reduced by 3-4 %.

C.3 Evaluation Matrix

An evaluation matrix was used to help determine which concept we would take forward to the building process.

Table C.1: Concept Evaluation Matrix

		Parallel Plates	Buckets	Vertical Sections

Criteria	w_i	x_i	$w_i x_i$	x_i	$w_i x_i$	x_i	$w_i x_i$
Processing Rate	0.8	5	4	8	6.4	8	6.4
Ease of Build	0.6	4	2.4	5	3	9	5.4
Efficiency	1	9	9	8	8	9	9
Scalable	0.3	3	0.9	7	2.1	7	2.1
Easy Operation	0.4	9	3.6	6	2.4	9	3.6
Modular	0.4	7	2.8	9	3.6	9	3.6
Durability	0.5	6	3	6	3	8	4
K.I.S.S.	0.8	6	4.8	6	4.8	8	6.4
$\sum_i w_i x_i$			**30.5**		**33.3**		**40.5**

The processing rate is effected by how quickly the soil can be heated and then cooled. The 'Buckets' and 'Vertical Sections' concepts use both convection and conduction to transfer heat to and from the soil, while the 'Parallel Plate' concept uses only conduction, thus it is slower. The convection heating concepts are more scalable than the conduction concept as the air stream velocity can be increased in larger systems to increase the heat transfer. In contrast, increasing the plate separation in the conduction concept will slow down the heat conduction.

All designs will be relatively easy to build, but the plate concept contains plates which have to be able to carry a fluid internally, increasing its complexity. They all have the potential to have high efficiency, with the buckets scoring less as when they move along a spot fittings will need to be changed, which could allow heat to be lost out of the system. For this same reason the buckets score lower than the other two concepts, in the easy operation criteria; the other two can be operated simply by adjusting feed rate and pulling sliders in and out.

The concepts are all able to be built in a modular way, using heat sources and fittings etc. which can be swapped in and out. The plates concept scored lower, as once the plates themselves have been built it would require considerable effort to change them, relative to changing parts on the other concepts. The plates and buckets concepts scored slightly lower in terms of durability. Soil is an abrasive material so would wear away at the plates, as it would be flowing constantly and the gap between the plates is small. Buckets are less durable than the vertical sections, due to the fittings having to be constantly closed as the containers move down a spot.

'Keep It Simple Stupid' is a criteria set by our client. Basically he wants the 'proof of concept' unit to be as simple as possible as in the real world, *i.e.* on a farm, the machine would need to be resistant to breakage and easy to fix if need be. The 'Vertical Sections' concept scores the highest here due to the reasons above that make it; the easiest to build, modular, easy to operate and durable.

The team has therefore decided to pursue the 'vertical sliders' concept.

Appendix D

Theoretical Results

D.1 Conduction

D.1.1 Heat Conduction in Soil from a Hot Plate

The transient heat conduction through a uniform medium is found by considering conservation of energy and given by

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T), \tag{D.1}$$

where C is the heat capacity of the soil, ρ is the density, k is the thermal conductivity, and T is the temperature.

A Matlab code was written to calculate the transient heat conduction for the soil to reach at least 200 °C. The soil area is assumed to have symmetrical heating from both sides and is therefore modelled as a hot plate to insulated wall, using half of the gap value as the length. The heat source was a hot plate set at 400 °C, and a gap of 20 mm between the plates and constants of C_{p} = 800 J/kg.K, K = 1.2 W/m, soil density, ρ = 1200 kg/m^3 [2]. The results are seen in Figure D.1.

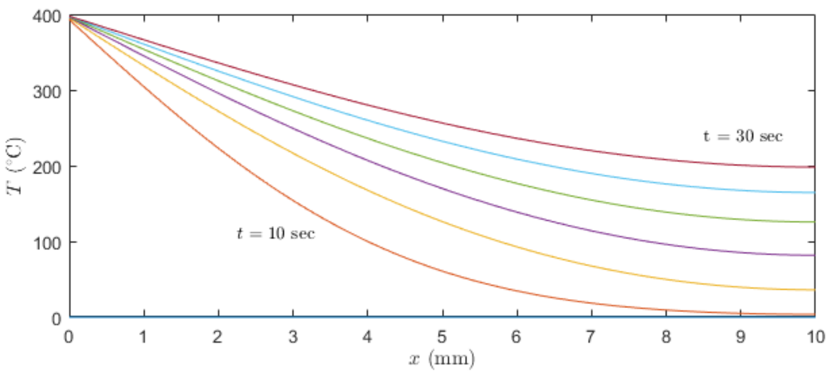


Figure D.1: Plot showing the temperature distribution between a heated plate at 400 °C and an insulated boundary, with times varying from 10 to 30 seconds.

In addition to the transient heat conduction model, a Comsol simulation of the one-dimensional heat response was made to ensure the previous results were appropriate. For a soil thickness of 40 mm and a set plate temperature of 500 °C, heating to a minimum of 200 °C takes approximately 120 seconds. The results can be seen in Appendix D.3.

To achieve heat recycling, the temperature of the plates could be increased in steps in the heating half, and then deceased in steps in the cooling half. Cycling fluid through pairs of plate sections top and bottom would keep the pairs of plate sections in thermal equilibrium. Figure D.2 shows the response to the stepped temperature plate system. The system consists of 20 mm separated plates and a flow rate of 5 mm/s. The overall height is 2 m.

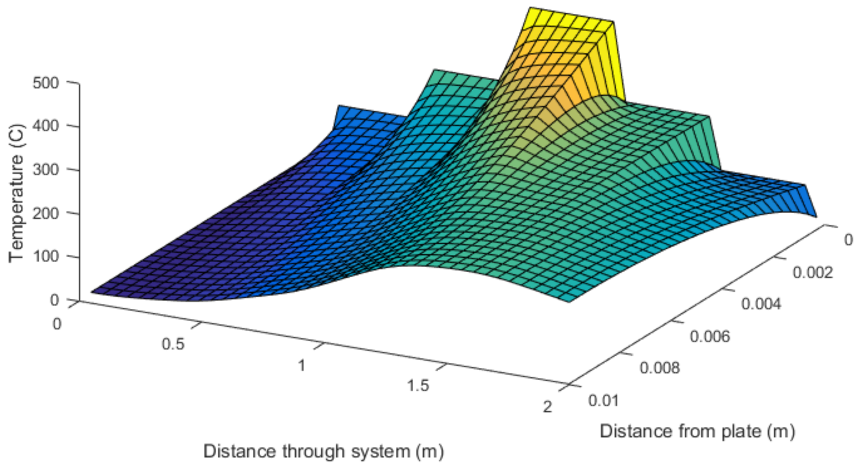


Figure D.2: 3D graphical view of the soil heat distribution as the plate temperatures are stepped and soil moving vertically through the device.

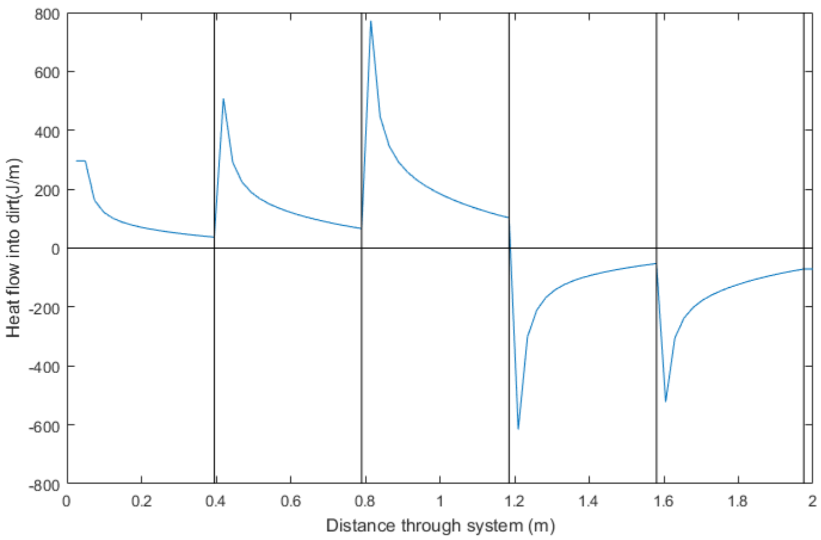


Figure D.3: Plot with heat flow rate into soil with stepped hot plates.

The team was concerned with jamming of the soil between the vertical plates, so a test rig was constructed by spot welding steel plates 20 mm apart from each other. Soil was then fed through the plates in different manners to see the response of the flow. If the soil was compacted, then there was jamming and if the test rig was shaken the jammed soil remained. It was only when the plates were hit did they release the soil.

D.1.2 Basic Conduction Simulation

Times to heat soil (Conduction) w/ varying plate temp, plate gap, thermal diffusivity

Max	alpha =	1.91E-06							
			Gap	1 cm	2 cm	3 cm	4 cm	5 cm	
		Plate Temp							
		250		9.4	37.6	84.7	150.5	235.2	
		300		6.8	27.1	60.9	108.3	169.2	
		350		5.5	21.9	49.3	87.7	137.1	
		400		4.7	18.8	42.3	75.2	117.6	
		450		4.2	16.7	37.6	66.8	104.3	
		500		3.8	15.2	34.1	60.6	94.7	values in seconds

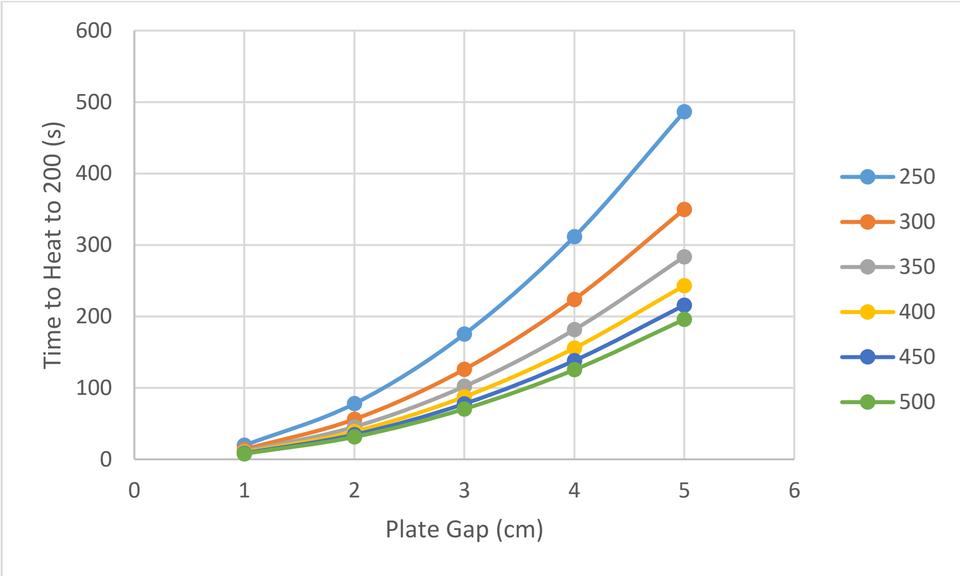
Upper Mid	alpha =	1.01E-06							
			Gap	1 cm	2 cm	3 cm	4 cm	5 cm	
		Plate Temp							
		250		17.7	70.9	159.5	283.6	443.2	
		300		12.7	51	114.7	204	318.7	
		350		10.3	41.3	93	165.3	258.2	
		400		8.9	35.4	79.7	141.8	221.5	
		450		7.9	31.4	70.7	125.8	196.5	
		500		7.1	28.5	64.2	114.2	178.4	values in seconds

Mean	alpha =	9.21E-07							
			Gap	1 cm	2 cm	3 cm	4 cm	5 cm	
		Plate Temp							
		250		19.5	77.8	175.1	311.4	486.4	
		300		14	56	125.9	223.9	349.8	
		350		11.3	45.4	102	181.4	283.5	
		400		9.7	38.9	87.5	155.6	243.1	
		450		8.6	34.5	77.7	138.1	215.7	
		500		7.8	31.3	70.5	125.3	195.8	values in seconds

Lower Mid	alpha =	5.19306E-07							
			Gap	1 cm	2 cm	3 cm	4 cm	5 cm	
		Plate Temp							
		250		34.5	138.1	310.7	552.4	863.1	
		300		24.8	99.3	223.5	397.2	620.7	
		350		20.1	80.5	181.1	321.9	502.9	
		400		17.3	69	155.3	276.1	431.4	
		450		15.3	61.2	137.8	244	382.8	
		500		13.9	55.6	125.1	222.4	347.5	values in seconds

Min	alpha =	1.17188E-07							
			Gap	1 cm	2 cm	3 cm	4 cm	5 cm	
		Plate Temp							
		250		153	612	1376	2448	3825	
		300		110	440.1	990	1760	2751	
		350		89.2	356.6	802	1426	2229	
		400		76.5	305.8	688	1223	1912	
		450		67.8	271.4	610	1086	1696	
		500		61.6	246.4	554	985	1540	values in seconds

Plot of time to heat w/ mean thermal diffusivity and varying plate gap and temperature



D.2 Convection

D.2.1 Fluid Flow in Porous Media

Henry Darcy (1856) investigated steady-state flow in a uniform media and observed a linear relationship between fluid velocity and applied pressure

$$\boldsymbol{u} = -\frac{K}{\mu}\nabla P, \tag{D.2}$$

known as Darcy's Law. The K parameter is called the specific permeability of the porous medium and μ is the viscosity of the fluid.

A well used approximation for the permeability is given by

$$K = \frac{d^2\varphi^3}{180(1-\varphi)}, \tag{D.3}$$

known as the Kozeny-Carman relationship. The d parameter is the diameter of the particles and φ is the porosity of the medium. This relationship is only really valid when the particles in the porous media are spherical and the diameters of the spheres, d, fall in to a narrow range. Despite this it is applied widely as it is the best of the simple approximations available.

This level of approximation should be suitable to the application as the variability of the parameters across different types of soil is fairly large. The Kozeny-Carman equation will give us approximate values for scoping air blowers for use in the 'Vertical Sections' concept.

D.2.2 Heat Transfer in Porous Media

For heat transfer in a homogeneous porous-medium with uniform fluid flow, we consider the energy change of a closed volume much larger than the pore and grain sizes, but much smaller than the size of the bulk. The fluid and the solid are considered separately, and only conduction and convective heat transfer are allowed.

The heat transfer is then governed by

$$(1-\varphi)(\rho C)_{\mathrm{s}}\frac{\partial T_{\mathrm{s}}}{\partial t} = (1-\varphi)\nabla\cdot(k_{\mathrm{s}}\nabla T_{\mathrm{s}}) + h(T_{\mathrm{f}} - T_{\mathrm{s}}) \tag{D.4}$$

and

$$\varphi(\rho C_{\mathrm{P}})_{\mathrm{f}}\frac{\partial T_{\mathrm{f}}}{\partial t} + (\rho C_{\mathrm{P}})_{\mathrm{f}}\boldsymbol{u}\cdot\nabla T_{\mathrm{f}} = \varphi\nabla\cdot(k_{\mathrm{f}}\nabla T_{\mathrm{f}}) + h(T_{\mathrm{s}} - T_{\mathrm{f}}) \tag{D.5}$$

The first term on the LHS of the solid equation is conduction in the solid, while the second term is thermal exchange between the solid and fluid. Similar terms appear in the fluid equation with an extra term that describes convective heat transfer that depends on the average fluid velocity.

Approximate expressions exist for the heat transfer coefficient, h, but a first level approximation is to assume that it is large and so $T = T_{\mathrm{f}} = T_{\mathrm{s}}$, *i.e.* the fluid and solid are in local equilibrium. The above equations then simplify to

$$(\rho C)_{\mathrm{eff}} \frac{\partial T}{\partial t} + (\rho C_{\mathrm{P}})_{\mathrm{f}} \boldsymbol{u} \cdot \nabla T = \nabla \cdot (k_{\mathrm{eff}} \nabla T), \tag{D.6}$$

where

$$(\rho C)_{\mathrm{eff}} = (1 - \varphi)(\rho C)_{\mathrm{s}} + \varphi (\rho C_{\mathrm{P}})_{\mathrm{f}}, \tag{D.7}$$

and

$$k_{\mathrm{eff}} = (1 - \varphi) k_{\mathrm{s}} + \varphi k_{\mathrm{f}}. \tag{D.8}$$

Equation D.6 was solved numerically for an average soil (somewhere between sandy and clayey, see Appendix B.1) and STP air at 500 °C. With average air velocity of $u = 1$ m/s, the temperature distributions shown in Figure D.4 were obtained. The rate of heat transfer is significantly increased compared to pure conduction. All of the soil in the 20 mm column of soil has reached the 200 °C requirement in less than 35 seconds.

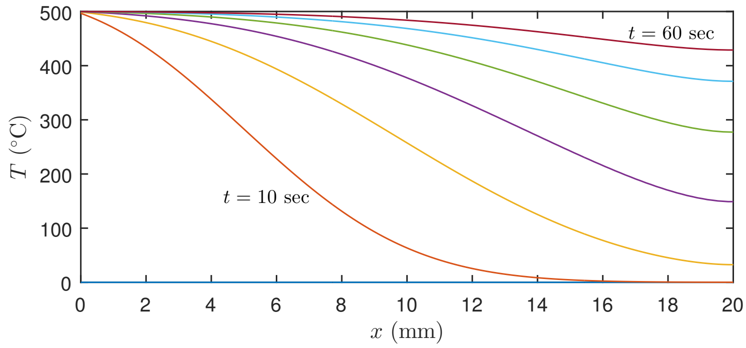


Figure D.4: Basic simulation of convective heating of soil via air at 500 °C.

D.3 Comsol Simulations

Comsol Simulation - Conduction

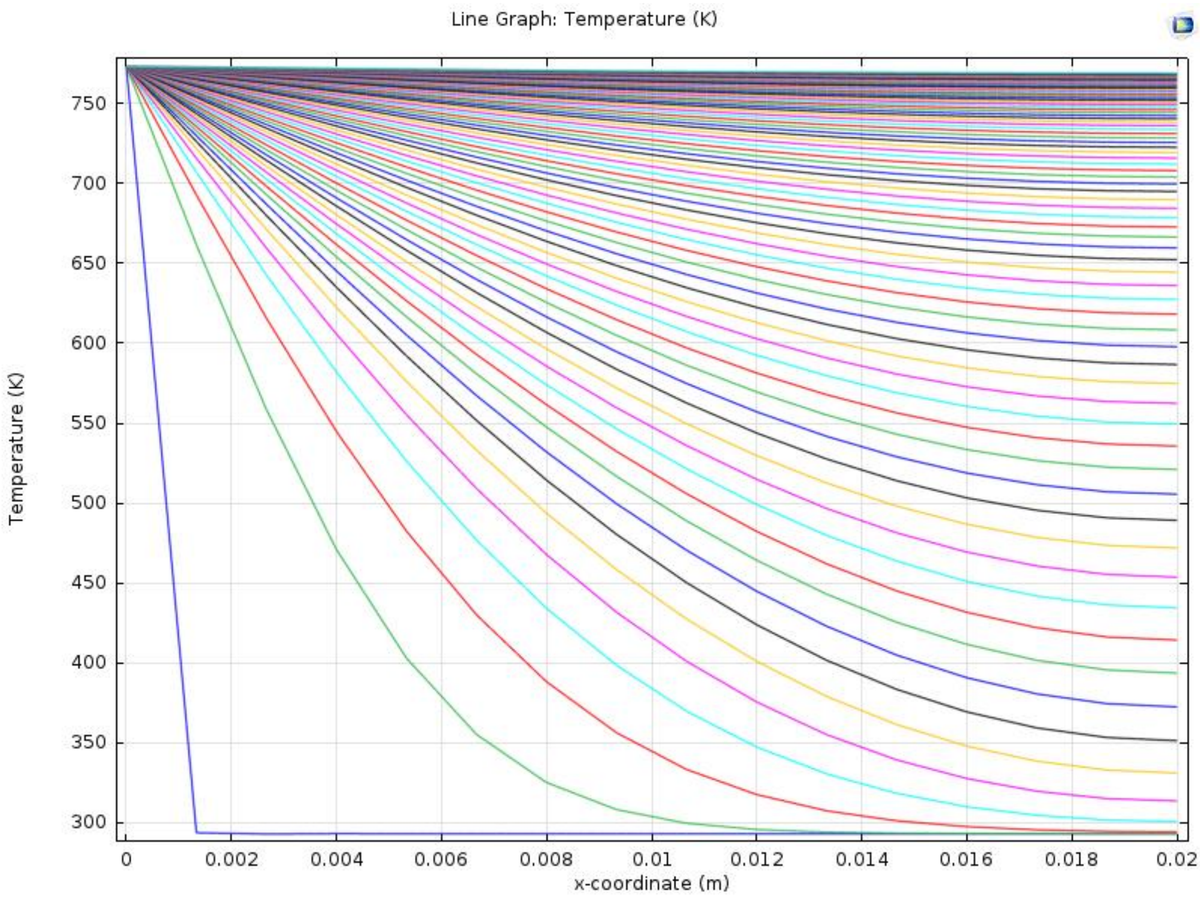
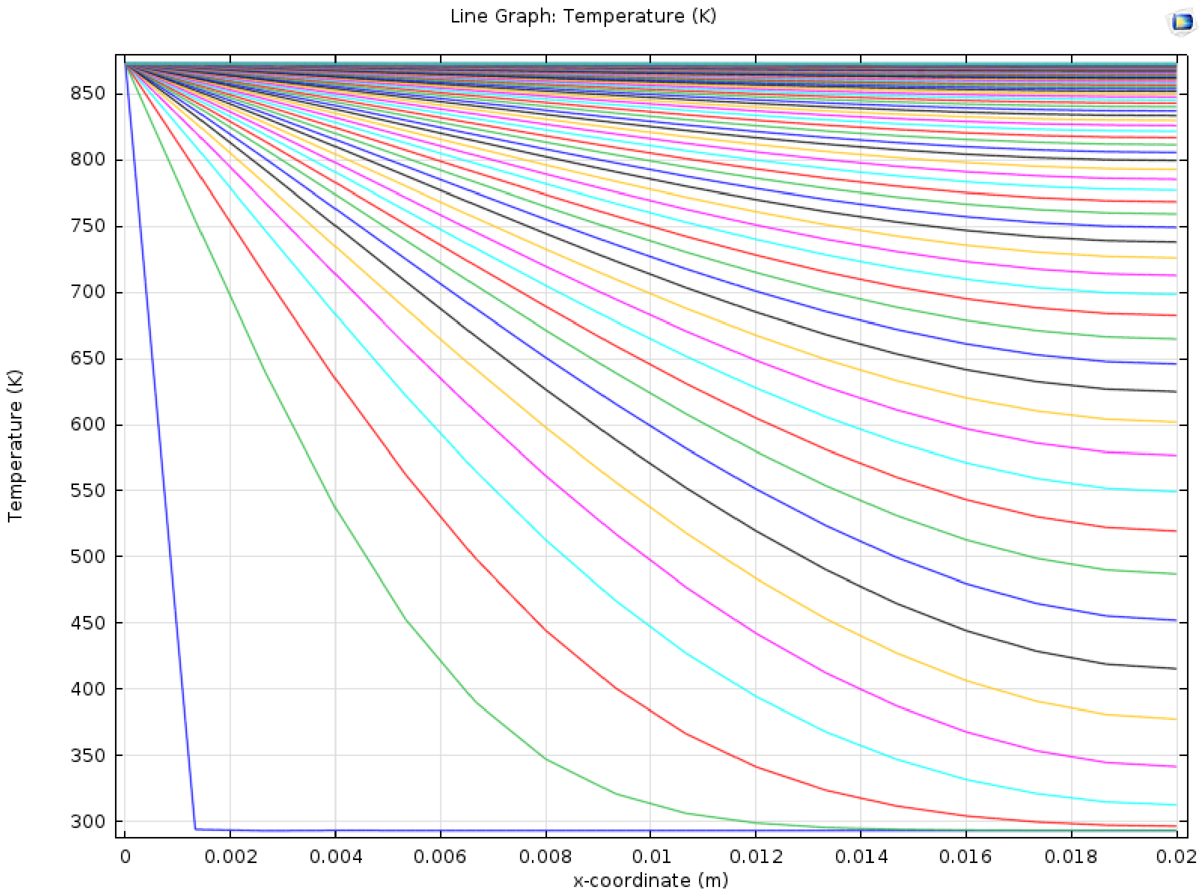
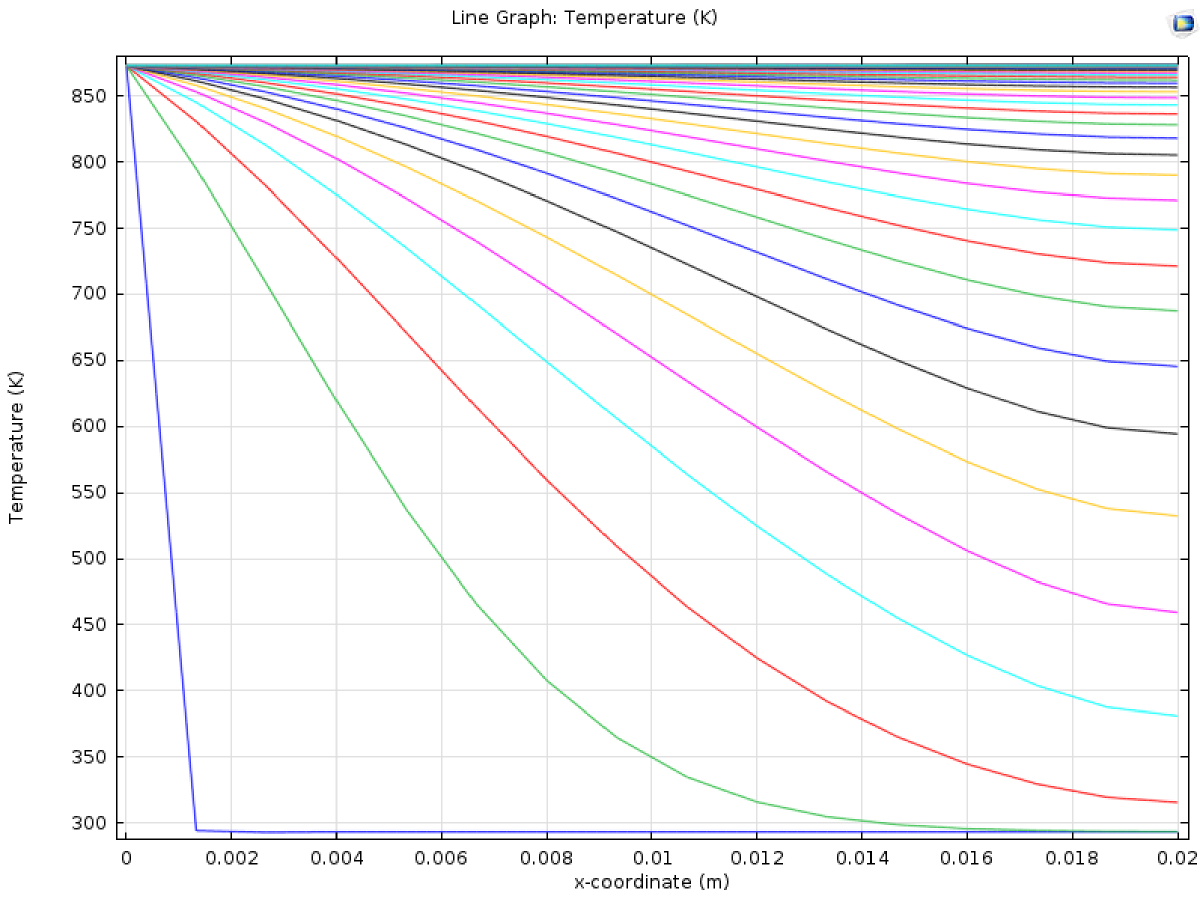


Plate temp of 500 deg. Heating through to 2 cm thickness. Time to 473K/200 deg. at 2cm: ≈ 120 sec.

Comsol Simulation – Convection



Steps of 10 seconds, air stream 600 deg. Heating through to 2 cm thickness. Flow speed of 0.25 m/s.
Time to 473K/200 deg. at 2cm: ≈ 80 sec.



Steps of 10 seconds, air stream 600 deg. Heating through to 2 cm thickness. Flow speed of 1 m/s.
Time to 473K/200 deg. at 2cm: ≈ 45 sec.

D.4 Burner

In order to understand how a burner behaves with different air fuel ratios and air flow rates the burners output temperature can be found by:

$$T_{\text{out}} = T_{\text{a}} + 2\frac{E_{\text{f}}}{((1 + R_{\text{af}})C_{\text{p}}} \text{ and } q_{\text{in}} = E_{\text{f}} M_{\text{air}} \tag{D.9}$$

These equations were derived through conservation of energy assuming complete burning of the fuel and that the effect of the difference between the specific heat of the air and fuel is minimal. These calculations were used to find the flow-rate and temperature with an air to fuel ratio of 15.5 to 1, and a burner output of 2 kW. Where $T_{\text{a}} = 25°\text{C}$ is the temperature of the air going into the burner, $C_{\text{p}} = 1.026$ kJ/kgK is the specific heat density of air[10]. $R_{\text{af}} = M_{\text{air}}/M_{\text{fuel}}$ is air to fuel mass ratio and $E_{\text{f}} = 50$ MJ/kg is the energy density of LPG fuel[11]. The output temperature under these conditions was 2849 °C and a flow rate of 0.0025 kg/s.

To try and get an idea of the effectiveness of a simple heat exchanger (so that the burner fumes and soil don't mix) a numerical calculation for a tube in tube heat exchanger was derived assuming steady state and the air being a point mass line. The calculations were for a 1 m long, 50 mm tube holding the hot gas inside a 100 mm outer tube holding the air that was being heated. The air speed used was 0.005 kg/s which was calculated as the flow rate for an air to fuel ratio of 15.5, a 2 kW burner, 50 % efficiency, and a fuel energy density of 46 MJ/kg [1]. The calculations presented strange results as the heat exchanger was found to be 99 % efficient (with turbulent flow), which is much higher than what would be expected. The heat exchanger Matlab code was not looked into further because the design requirements changed, meaning that a heat exchanger was not needed and a hot air gun would be used instead.

Appendix E

Results

Table E.1: Temperatures with no heat recycling

time	sample 1	sample 2	sample 3	sample 4	average
0:00	47	48	49	41.75	46.4
0:30	68	67.5	65	54	63.6
1:00	77	77.25	74.5		76.3
1:30	81.25	82	79		80.8
2:00	84.25	84.5	82	78.5	82.3
2:30	86.5	86.5	84.75	80	84.4
3:00	88	87.75	86.75	82.25	86.2
8:00	93.5	91.5	91.75	90	91.7
15:00	96	91.25	90.75	90	92

Table E.2: Temperatures with heat recycling. sample 1

	top section soil	middle section soil	bottom section soil	top air	bottom air
0:00	52	79.25	73		
0:30	57	86.5	71	55	55
1:00	61.5	89	68.5	55	55
1:30	68	89.25	64	55	55
2:00	68	90	64	56	56
2:30					
3:00	73	90.5	62	56	56
8:00	85	91.5	55	56	56
15:00	88.75	94	52.25	55.5	56.5

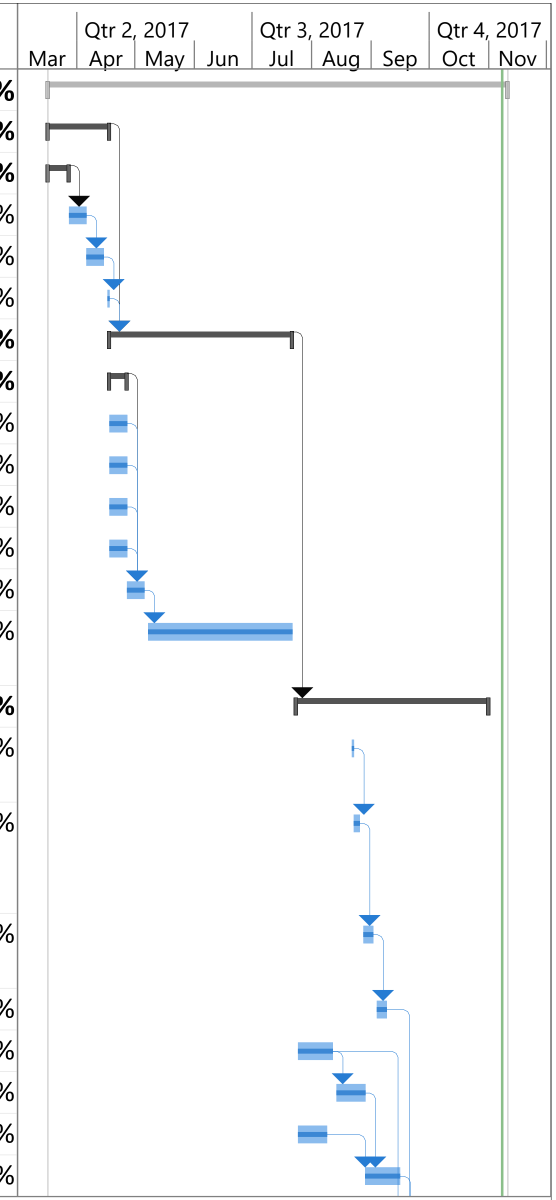
Table E.3: Temperatures with heat recycling. Sample 2

	top section soil	middle section soil	bottom section soil	top air	bottom air
0:00	53	79	79	55.5	55.5
0:30	59.25	84.25	74.25	55	55.25
1:00	63.25	87	70	55	55
1:30	66	88.25	67	54.75	54.75
2:00	68.25	89.25	65	54.5	54.5
2:30	70.25	90.5	61.7	54	54.25
3:00	72.5	90.5	61.7	54	54.25
8:00	80.5	92	54.5	52.5	53.5
15:00	87.25	92.25	51.5	51.75	53

Appendix F

Gantt Chart

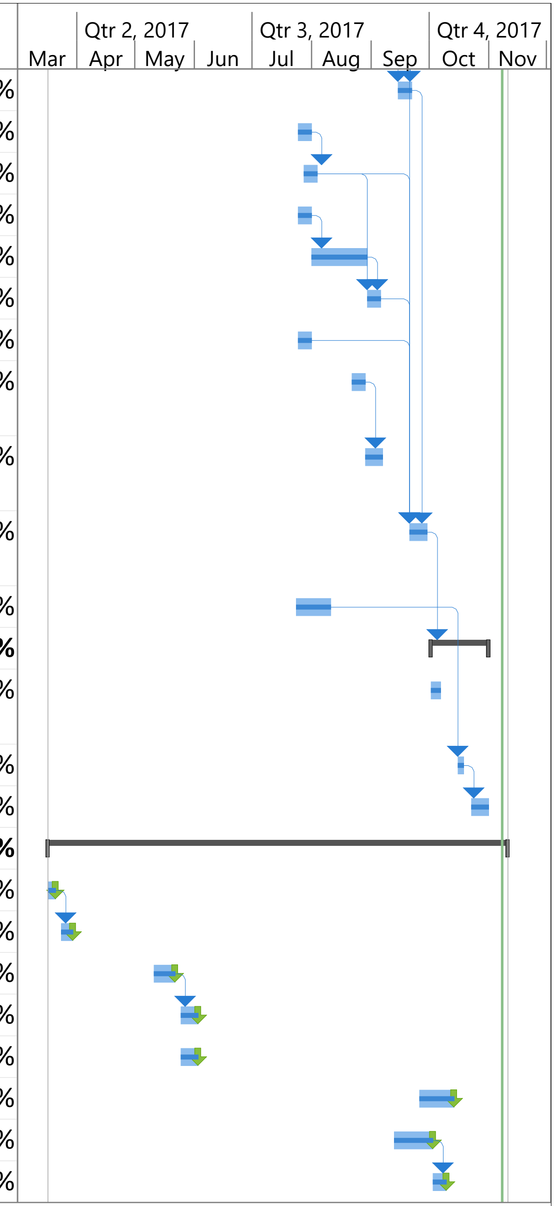
ID	Task Name	Start	Finish	Duration	Predecessors	% Complete
0	**ENME408 honors project**	**17/03/17**	**10/11/17**	**171 days**		**100%**
1	**Research**	**17/03/17**	**17/04/17**	**22 days**		**100%**
2	**Background Research**	**17/03/17**	**27/03/17**	**7 days**		**100%**
6	Concept generation	28/03/17	05/04/17	7 days	2,3,4,5	100%
7	Concept selection	06/04/17	14/04/17	7 days	6	100%
8	Identify sub-functions	17/04/17	17/04/17	1 day	7	100%
9	**Concept development**	**18/04/17**	**21/07/17**	**69 days**	**1,8**	**100%**
10	**Theoretical modeling**	**18/04/17**	**26/04/17**	**7 days**		**100%**
11	Energy calculations	18/04/17	26/04/17	7 days		100%
12	Heat loss /insulation calculations	18/04/17	26/04/17	7 days		100%
13	Flow rate calculations	18/04/17	26/04/17	7 days		100%
14	heat transfer rate equations	18/04/17	26/04/17	7 days		100%
15	Sub function design selection	27/04/17	05/05/17	7 days	10,11,12,13,14	100%
16	Experimenting with different ideas to find something that works	08/05/17	21/07/17	55 days	15	100%
17	**Prototype construction**	**24/07/17**	**31/10/17**	**72 days**	**9**	**100%**
18	Buy New heat gun with temperature control	22/08/17	22/08/17	1 day		100%
19	Build new container for heat gun electronics to enable recycling air through heat gun	23/08/17	25/08/17	3 days	18	100%
20	Get electrical technician to wire up heat gun	28/08/17	01/09/17	5 days	19	100%
21	Mount heat gun	04/09/17	08/09/17	5 days	20	100%
22	Order blowers for recycling heat	25/07/17	11/08/17	14 days		100%
23	Mount air recycling blowers	14/08/17	28/08/17	11 days	22	100%
24	Order silicon pipes	25/07/17	08/08/17	11 days		100%
25	Mount heat recycling pipes	29/08/17	15/09/17	14 days	23,24	100%



Project: ENME408 honors proje
Date: 08/11/17

Task | Summary | Project Summary | Deadline

ID	Task Name	Start	Finish	Duration	Predecessors	% Complete
26	Test heat recycling system air flow	15/09/17	21/09/17	5 days	25,22	100%
27	Make heat recycling sections	25/07/17	31/07/17	5 days		100%
28	Attach heat recycling sections	28/07/17	03/08/17	5 days	27	100%
29	Draw soil gate in CAD soft where	25/07/17	31/07/17	5 days		100%
30	Get soil gates made by technicians	01/08/17	29/08/17	21 days	29	100%
31	Attach soil gates to prototype	30/08/17	05/09/17	5 days	30,28	100%
32	Make stand to hold prototype	25/07/17	31/07/17	5 days		100%
33	Buy/acquire final temperature probes and temperature display screen	22/08/17	28/08/17	5 days		100%
34	Get temperature sensing and displaying working	29/08/17	06/09/17	7 days	33	100%
35	Prototype testing with heat recycling system	21/09/17	29/09/17	7 days	32,28,26,31,21	100%
36	Purchase insulation	24/07/17	10/08/17	14 days		100%
37	**Refine prototype**	**02/10/17**	**31/10/17**	**22 days**	**35**	**100%**
38	Make temperature sensor and display container	02/10/17	06/10/17	5 days		100%
39	Install insulation	16/10/17	18/10/17	3 days	36	100%
40	Re-test the prototype	23/10/17	31/10/17	7 days	39	100%
41	**Reporting**	**17/03/17**	**10/11/17**	**171 days**		**100%**
42	Work on proposal (draft)	17/03/17	20/03/17	2 days		100%
43	Work on proposal (final)	24/03/17	29/03/17	4 days	42	100%
44	Mid year report (draft)	11/05/17	21/05/17	7 days		100%
45	Mid year report (final)	25/05/17	02/06/17	7 days	44	100%
46	Mid year presentation	25/05/17	02/06/17	7 days		100%
47	Final year presentation	26/09/17	13/10/17	14 days		100%
48	Poster (draft)	13/09/17	02/10/17	14 days		100%
49	Poster (final)	03/10/17	09/10/17	5 days	48	100%



Project: ENME408 honors proje
Date: 08/11/17

Task | Summary | Project Summary | Deadline

ID	Task Name	Start	Finish	Duration	Predecessors	% Complete
50	End of year report (draft)	29/09/17	27/10/17	20 days		100%
51	End of year report (final)	30/10/17	10/11/17	10 days	50	100%

Project: ENME408 honors proje
Date: 08/11/17

Task
Summary
Project Summary
Deadline