Sensitivity Analysis for a Plug-Flow Anaerobic Digester

A Master of Engineering Project

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ABSTRACT

A parametric study on a plug-flow anaerobic digester was performed in order to determine the effect of certain design variables on two digester responses: heat requirement and biogas production. Each parameter considered was assigned low, reference, and high values that were based on common digester designs. Using a previously-built simulation that predicted heat requirement and biogas production based on the models presented in Gebremedhin et al. (2005) and Gebremedhin and Inglis (2007), every combination low, reference, and high values was simulated. A Visual Basic program was used to sort the resulting 3 million plus data points in order to determine the rates at which each variable affected heat requirement and biogas production. These rates were then used to compare the design variables' effects on each digester response.

In regards to heat requirement, the insulation variables (floor insulation thickness, insulation conductivity, and wall insulation thickness) had the largest effect. On the other hand, variables that were not associated with digester building materials (hydraulic retention time, manure flow rate, ambient temperature, and digester radius) had a negligible effect. Considering biogas production, hydraulic retention time exhibited a significant negative relationship with the rate of biogas production while the effect of manure flow rate was negligible.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Professor Gebremedhin, for his guidance and encouragement throughout the entire research process. He has not only helped me accomplish this project, but has also helped steer me in the direction that I will continue to develop both academically and professionally.

I would also like to thank my wonderful family for their love and support. Without you, I would not be where I am today. I truly thank you for the all of the happiness that you bring into my life.

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1. INTRODUCTION

1.1 General

This paper performs a parametric study on a plug-flow anaerobic digester by examining input variables that affect the digester's heat requirement and biogas production. Through this parametric study, insight can be gained on optimal digester design by ranking each input variable's effect on the response variables (heat requirement and biogas production). This sorting process enables design priorities to be more clearly outlined and maximum digester efficiency to be achieved. In the anaerobic digester modeled, maximum efficiency is reached by minimizing heat requirement and maximizing biogas production.

Through a parametric study, variables with the largest effect on the response variables can be isolated. Based on each input variable's quantitative influence on the response variable, an optimal amount of focus and investment in that variable can be determined. The larger the input variable's potential effect, the more important it is to manipulate it advantageously by assigning a value that is sufficient enough to secure a positive effect on the response variable. If the response variable is highly sensitive to variations in an input variable, then it is crucial to ensure that the digester design does not implement a value for the input variable that leads to drastic adverse effects.

Equally important as determining the variables with the greatest effect on the response variables, a parametric study also determines the variables that have a minor or negligible effect on the response variable. Figuring out these variables can save time and money by preventing unnecessary investment energy. Furthermore, by disregarding input variables with negligible effects on a certain response variable, the design process is condensed and simplified. These input variables can now be manipulated to increase digester productivity through other response variables that are significantly affected.

This parametric study approximates the rate of change of an input variable versus the response variable. Input variables that induce a high rate of change are considered the variables which cause a large effect on the response variable, and the variables that generate a small rate of change are considered the variables with a minor or negligible effect. However, beyond determining average rates of change, a parametric study can further be used to gain insight on the type of relationship exhibited between the input and response variables. In calculating the average rate of change, these two variables are assumed to share a linear relationship, but this may not be the most accurate estimation. By varying each input variable and observing the resulting response variable values, an appropriate relationship (linear, exponential, etc.) can be predicted. If the input variable is relatively significant, this relationship is crucial in maximizing digester efficiency.

Due to the numerous variables to consider in designing a plug-flow anaerobic digester, the practicality of this study is evident. It narrows the focus on the heat requirement and biogas production aspects of digester design by approximating the degree of impact of each input variable. Furthermore, it predicts relationships between input variables and heat requirement or biogas production, which can be used in conjunction with cost models to determine financially optimal values for each input variable. Therefore, this study is an essential step in designing a practical digester.

1.2 Objectives

1) Conduct sensitivity analysis of independent variables on two digester responses—(a) heat requirement for digester function, and (b) biogas production.
2) Rank the independent variables based on their effects (sensitivity) on the digester responses.
3) Evaluate trends between input and response variables to determine if any relationship is highly non-linear.

2. LITERATURE REVIEW

Variables Affecting Heat Requirement

Digester heat requirement is significantly influenced by the amount of energy used to heat incoming manure to the digester operating temperature. Since ambient temperature governs the temperature of the incoming manure, ambient temperature in turn affects heat required to heat this manure to the digester operating temperature (Srivastava, 1987). Higher ambient temperatures should thus imply less heat required to heat the influent manure. Studies conducted by Golueke (1977) suggests that temperature has a linear relationship with digestion efficiency between 86-95°F, where it begins to level off and reach a maximum between 95- 104°F. Therefore, although digester operating temperature also affects heat requirement, the model discussed herein assumes a constant operating temperature of 100°F (or 37.78°C). Golueke also suggests that manure flow rate also affects the heating requirement, because a higher manure flow rate means a greater volume of manure that requires heating.

When the digester operating temperature is higher than ambient temperature and wall and floor temperatures, total heat requirement can also be influenced by heat loss through the digester's cover, walls, and floor. Digester construction material has a significant bearing on heat loss, because each material causes a different heat transfer rate (Srivastava, 1987). Srivastava (1987) further suggested that it is important to ensure proper insulation and underground placement (below grade, partially below grade, or above grade) to reduce heat loss. However, in the model presented, the digester is assumed to be placed completely below grade. Srivastava (1987) also reported the effect of digester size on heat loss, deducing that size directly affects the surface area of the digester. A larger digester of the same shape implies a larger surface area, meaning the area that heat can escape through is increased. Therefore, heat loss is expected to rise with digester radius, holding digester depth constant.

In a study done by Gebremedhin et al. (2005), heat required to maintain the digester was 2.5 times greater on January 20th than July 20th, where the ambient temperature was -5°C and 30°C, respectively. This sizeable difference in heat requirement further demonstrates ambient temperature's effect on heat requirement. This study conducted by Gebremedhin et al. (2005) also examines the heat loss through the floor and walls of the digester. They reported that on January 20th 23.7% of total heat loss occurred through the digester walls and 10.5% through the floor, and on July 20th, these numbers were 30.2% through the walls and 27.4% through the floor. Gebremedhin et al. (2005) reported that the wall temperature was closer to the floor temperature in summer than in winter, causing a decreased temperature gradient through the walls in summer, which approached the even lesser temperature gradient through the floor. As a result, the percentage of total heat loss through the floor and walls was significantly closer in summer when ambient temperature was high.

Variables Affecting Biogas Production

Fannin and Biljentina (1987) stated that a high percent of volatile solids breakdown could be obtained at longer hydraulic retention times, and that high methane production with a low percent of volatile solids breakdown could be obtained at shorter hydraulic retention time coupled with a faster manure flow rate. They explained that volatile solids were broken down at a faster rate when the amount of volatile solids was high. As volatile solids were degraded, the decreasing amount of volatile solids led to a continually slower rate of degradation. Therefore, while longer retention times promoted a greater percentage of volatile solids degradation, the rate of volatile solids degradation decreased. A shorter hydraulic retention time was suggested to maximize overall biogas production, even though a longer hydraulic retention time promotes a higher biodegradation of manure. Considering digester economics, Fannin and Biljentina (1987) recommended a longer retention time when influent is expensive to obtain and a shorter retention time when it is cheaper.

Heat Requirement and Biogas Production Model

A simulation was created to predict heat requirement and biogas production based on the model presented in Gebremedhin et al. (2005) and Gebremedhin and Inglis (2007), respectively. The simulation used user-inputted variables to calculate heat loss through the walls, floor, and cover (including solar heat gain), heat required to heat influent manure, and predicts biogas production.

3. MODEL DEVELOPMENT

3.1 Problem Description

Sensitivity analyses were conducted on simulation results, which were created from the model described in *Section 2*. In obtaining simulation results, three values were assigned for each variable, and they were: low, reference, and high values shown in *Table 3.1*. Radii for cylindrical shaped digesters were varied as shown in Table 3.2. These variables were inputted into the model, ensuring that every combination of the three levels (low, reference, and high) was simulated. The resulting output contained 3,188,700 data points spread over 54 Microsoft Excel spread sheets. The goal was to extract useful information from these data points with respect to heat requirement and biogas production.

3.2 Assumptions

<u>Digester Assumptions</u>

1) The digester studied was built completely below grade with the top cover exposed to ambient air.
2) The Digester depth = 5.8m.
3) The ground surrounding the digester is not frozen.
4) Heat loss through the cover is constant.
5) Solar heat gain is constant.
6) The digester is large enough to contain the influent for the specified hydraulic retention time.
7) The digester geometry is either rectangular or cylindrical.
8) The digester is maintained at an operating temperature of 37.78°C.
9) There is no heat generation within the digester.

<u>Environment Temperature Assumptions</u>

10) Deep ground temperature (>5.8 m deep) is below the average ambient temperature.

11) Deep ground temperature (>5.8 m deep) is assumed to be the average of yearly minimum and maximum temperatures.

12) Ambient temperature is assumed to be the average of monthly minimum and maximum temperatures.

13) The wall-ground interface temperature is equal to the average of ambient temperature and deep ground temperature (>5.8 m deep).

14) The floor/ground interface temperature is equal to the deep ground temperature (>5.8 m deep).

Influent Manure Assumptions

15) Influent manure is comprised of 12% of solids by volume

16) Total solids is comprised of 83% of volatile solids by volume

Other Variable Assumptions

17) All input variables given in Tables 3.1 and 3.2 are assumed to have linear relationships with digester heat requirement.

18) Only hydraulic retention time and manure flow rate affect biogas production.

3.3 Input Variables

Table 3.1: Input variables which include: low, reference, and high values

Input Variable	Units	Low	Reference	High
Ambient Temperature	Deg. C	5	19	30
Hydraulic Retention Time	Days	8	22	40
Manure Flow Rate	m^3/day	40	60	120
Material Thickness				
Wall Thickness	m	0.2	0.3	0.4
Floor Thickness	m	0.2	0.3	0.4
Wall Insulation Thickness	m	0.03	0.05	0.07
Floor Insulation Thickness	m	0.03	0.05	0.07
Material Conductivity				
Wall Conductivity	W/m*K	0.5	1.5	2.5
Floor Conductivity	W/m*K	0.5	1.5	2.5

Insulation Conductivity	W/m*K	0.05	0.15	0.25
Soil Properties				
Soil Specific Heat	kJ/kg*K	0.8	0.835	1.92
Soil Density	kg/m^3	1200	1450	1600
Soil Conductivity	W/m*K	0.19	1	1.94

Table 3.2: Digester dimension input values

Digester Dimension	Units	Values
Round		
Radius	m	16.23 , 12, 11.48, 8.51, 8.5, 7.26, 5.13, 4.19, 2.96
Rectangular		
Length	m	55.00
Width	m	13.75
Depth	m	5.8

3.4 Response Variables

In this study, the response variables are heat requirement (W) and biogas production (m^3/day)

3.5 Procedure

Conducting Sensitivity Analysis for Heat Requirement

A Visual Basic for Applications (VBA) program was written to calculate the average heat requirement at the high, reference, and low levels of each input variable listed in Tables 3.1 and 3.2 for each Excel spread sheet (*See Appendix for the VBA algorithm*). For each Excel sheet, the VBA program generated a table similar to Table 3.4 below. After the VBA program was run on all 54 Excel spread sheets, the calculated averages were manually combined to determine the overall averages of heat requirement. The “Number of Data Points” column in Table 3.3 was included in order to calculate the final averages for each variable. In the output table below, only a digester radius of 16.23 m was simulated, so the “Number of Data Points” column for the other eight radii have a value of 0.

Table 3.3: VBA program's Excel output file

Variable	Group	Value	Number of Data Points	Avg. Heat Req.*10^6 (W)
Ambient Temperature (°C)	High	30	20000	-31
	Reference	19	20000	249
	Low	5	19999	605
Hydraulic Retention Time (Days)	High	40	59999	275
	Reference	22	0	0
	Low	8	0	0
Manure Flow Rate (m^3/day)	High	120	59999	275
	Reference	60	0	0
	Low	40	0	0
Wall Thickness (m)	High	0.4	59049	275
	Reference	0.3	950	245
	Low	0.2	0	0
Floor Thickness (m)	High	0.4	20633	258
	Reference	0.3	19683	273
	Low	0.2	19683	294
Wall Insulation Thickness (m)	High	0.07	20633	270
	Reference	0.05	19683	274
	Low	0.03	19683	279
Floor Insulation Thickness (m)	High	0.07	20633	247
	Reference	0.05	19683	270
	Low	0.03	19683	308
Wall Conductivity (W/m*K)	High	2.5	20412	279
	Reference	1.5	19904	276
	Low	0.5	19683	268
Floor Conductivity (W/m*K)	High	2.5	20147	311
	Reference	1.5	19926	285
	Low	0.5	19926	228
Insulation Conductivity (W/m*K)	High	0.25	20007	332
	Reference	0.15	20007	285
	Low	0.05	19985	207

Soil Density (kg/m^3)	High	1600	20007	275
	Reference	1450	20007	275
	Low	1200	19985	275
Soil Specific Heat (kJ/kg*K)	High	1.92	19998	275
	Reference	0.835	19998	275
	Low	0.8	20003	275
Soil Conductivity (W/m*K)	High	1.94	19998	275
	Reference	1	20000	275
	Low	0.19	20001	275

Size	# Data Points	Avg. Heat Requirement
Radius 16.23 m	59999	2.75E8
Radius 11.48 m	0	0
Radius 2.96 m	0	0
Radius 12 m	0	0
Radius 8.5 m	0	0
Radius 8.51 m	0	0
Radius 7.26 m	0	0
Radius 5.13 m	0	0
Radius 4.19 m	0	0

The final averages for the low, reference, and high levels of each input variable listed in Tables 3.1 and 3.2 were plotted and best fit lines were generated assuming a linear relationship. The slopes of these best-fit lines were used to compare the relative effects of the input variables on heat requirement. Simulation results were also verified by comparing them to calculated results using the equations that were used in the model.

Conducting Sensitivity Analysis for Biogas Production

Biogas production rates for all nine combinations of hydraulic retention time and manure flow rate were sorted out from the 54 Excel spreadsheets. Since these two variables were the only ones affecting biogas production, there were only nine different simulation results for biogas production in all 54 spreadsheets. Once these values were retrieved, hydraulic retention time and manure flow rate were simultaneously plotted against biogas production to directly compare the effects of the input variables.

4. RESULTS AND DISCUSSION

4.1 Effects on Heat Requirement

4.1.1 Floor, Wall, Floor Insulation, and Wall Insulation Thicknesses

Heat flux through the floor (q''_{floor} in W/m^2) is calculated using the equation

$$q''_{floor} = \frac{(T_0 - T_f)}{\sum R_{floor}} \qquad (4.1)$$

T_0 is the operating temperature of the digester, which is held at 37.78°C. T_f is the temperature at the floor-ground interface (in Celsius). T_f is assumed to be taken at a point deep enough in the ground that the soil temperature is constant. This constant soil temperature is estimated by averaging the yearly maximum and minimum temperatures at the digester's location. $\sum R_{floor}$ is the total resistance to heat flow through the floor (in m^2K/W). It is calculated using the equation

$$R_{floor} = \frac{Thickness_{floor}}{DK_{floor}} + \frac{Thickness_{insulation,floor}}{DK_{insulation}} \qquad (4.2)$$

$Thickness_{floor}$ and $Thickness_{insulation}$ represents the thickness of the floor and insulation (in m), respectively. DK_{floor} and $DK_{insulation}$ represents the conductivity of the floor and insulation (in W/mK), respectively.

After obtaining the value for heat flux through the floor (q''_{floor}), it is multiplied by the area of the floor (A_{floor} in m^2) to calculate the total amount of heat loss through the floor.

$$Q_{floor} = q''_{floor} A_{floor} \qquad (4.3)$$

Heat flux through the wall is calculated using the equation

$$q''_{wall} = \frac{(T_0 - T_w)}{\sum R_{wall}} \qquad (4.4)$$

$\sum R_{wall}$ is the total wall resistance(in m^2K/W) and T_w represents the wall surface temperature (in Celsius). Since the digester in the model is built entirely below ground, the wall surface temperature is equal to the temperature at the wall-ground interface. Unlike the floor-ground interface, which is assumed to be deep enough where the ground temperature is constant, the temperature profile at the wall-ground interface varies from the ambient temperature, $T_{ambient}$ (in Celsius), at the ground surface to the constant deep ground temperature at the digester's depth of 5.8 m. In Equation 4.5 below, T_{ground} is the constant deep ground temperature (in Celsius). A mean temperature for the wall-ground interface was used to simplify the simulation. This mean temperature was obtained by averaging $T_{ambient}$ and T_{ground}, yielding the equation

$$T_w = \frac{T_{ambient} + T_{ground}}{2} \tag{4.5}$$

Resistance through the wall is calculated as

$$R_{wall} = \frac{Thickness_{wall}}{DK_{wall}} + \frac{Thickness_{insulation,wall}}{DK_{insulation}} \tag{4.6}$$

$Thickness_{wall}$ and $Thickness_{insulation}$ are the thickness of the wall and insulation (in m), respectively. DK_{wall} and $DK_{insulation}$ represents the conductivity of the wall and insulation (W/mK), respectively.

Heat loss through the wall is calculated as

$$Q_{wall} = q''_{wall} A_{wall} \tag{4.7}$$

q''_{wall} is the heat flux through the wall (in W/m^2) and A_{wall} is the total area of the walls (in m^2).

Simulation Results

After the simulation was run, the average heat requirement (in Watts) at the high, reference, and low levels of floor thickness, wall thickness, floor insulation thickness, and wall insulation thickness were extracted from 54 Excel spreadsheets. These average heat requirement values are given in Table 4.1.

Table 4.1: Simulation results for average heat requirement at the high, reference, and low levels of wall thickness, floor thickness, wall insulation thickness, and floor insulation thickness

Average Heat Requirement (Watts) * 10^6												
	Floor Thickness			Wall Thickness			Floor Insulation Thickness			Wall Insulation Thickness		
Variable Value (m)	0.4	0.3	0.2	0.4	0.3	0.2	0.07	0.05	0.03	0.07	0.05	0.03
Avg. Heat Req.	186	201	222	200	203	206	175	198	236	199	202	208

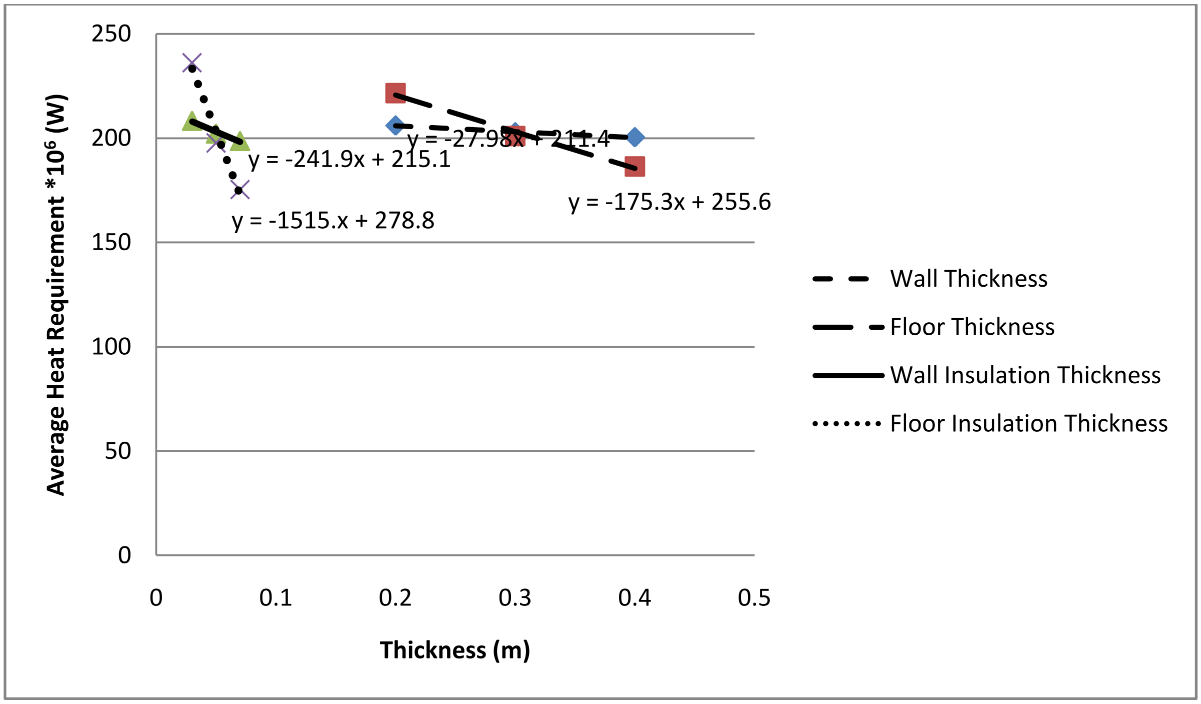

Figure 4.1: Average heat requirement as a function of wall thickness, floor thickness, wall insulation thickness, and floor insulation thickness.

<u>Trends</u>

As seen from Figure 4.1, each of the four variables exhibits a negative relationship with heat requirement. An increase in the resistance of the floor (R_{floor}) or wall (R_{wall}) obviously results in a decrease in heat loss, which in turn leads to a decrease in the heat requirement for digester function. Therefore, we expect both R_{floor} and R_{wall} to have a negative relationship with heat requirement. Since increasing both wall and floor thicknesses and both wall and floor insulation thicknesses lead to higher resistance values, heat requirement exhibits a negative relationship relative to each of these variables.

Floor/Wall Thickness versus Floor/ Wall Insulation Thickness:

Increasing floor insulation thickness causes average heat requirement to decrease 8.69 times faster than increasing floor thickness. Also, increasing wall insulation thickness causes average heat requirement to decrease 8.64 times faster than increasing wall thickness. Therefore, insulation has a greater effect on heat loss than the wall or floor material.

As shown in Table 3.1, the insulation of the floor and wall that was used in this model has a smaller conductivity than the floor or wall material by a factor of 10. Since insulation of the floor and wall in turn has a larger effect on floor and wall resistance, it is expected that insulation more greatly influences heat loss (or requirement). One would also intuitively expect insulation to have such a large relative effect on heat loss.

Floor versus Wall

By taking the ratio of the slopes of the best-fit lines in Figure 4.1, heat requirement decreases 6.25 times faster with an increase in floor thickness compared to an increase in wall thickness. Heat requirement decreases 6.28 times faster with an increase in floor insulation thickness compared to an increase in wall insulation thickness. Since heat requirement is significantly more sensitive to floor thickness than wall thickness and floor insulation thickness than wall insulation thickness, heat requirement is more sensitive to floor resistance than wall resistance.

In the model, the average temperature of the digester floor is lower than that of the walls, inducing a larger temperature gradient and more heat loss through the digester floors. The deep ground temperature (where ground temperature is constant) is sufficiently lower than the ambient temperature in this model, causing a lower temperature at the digester floor than the walls. However, this is not always the case, such as during winter time conditions when the ambient temperature is significantly lower than the deep ground temperature. Therefore, Figure 4.2 was created to visualize the impact of deep ground temperature on total heat loss through the walls and floor. Figures 4.3a and 4.3b were created to show how deep ground temperature was varied to create Figure 4.2, and also to demonstrate the temperature profiles through the ground at high and low deep ground temperatures. Heat losses through the walls and floor were manually calculated by varying deep ground temperature from 0-35°C, while using the reference values (see Tables 3.1 and 3.2) for each variable affecting heat flux through the wall and floor and the default rectangular digester dimensions to calculate wall and floor surface areas. These values are displayed in Table 4.2.

Table 4.2: Variables that were used in the manual calculations of heat loss through the walls and floor by varying deep ground temperature.

Variables used in Resistance Calculations	
Wall Thickness (m)	0.3
Wall Insulation Thickness (m)	0.05
Wall Conductivity (W/m*K)	1.5
Floor Thickness (m)	0.3
Floor Insulation Thickness (m)	0.05
Floor Conductivity (W/m*K)	1.5
Insulation Conductivity (W/m*K)	0.15
Calculated Resistance	
Wall Resistance (m^2/m*K)	0.533
Floor Resistance (m^2/m*K)	0.533

Variables used in Temperature Calculation	
T_0 (C)	37.78
$T_{ambient}$ (C)	19

Variables used in Surface Area Calculation	
Length (m)	55.00
Width (m)	13.75
Depth (m)	5.8
Calculated Surface Area	
Wall Surface Area (m^2)	797.5
Floor Surface Area (m^2)	756.25

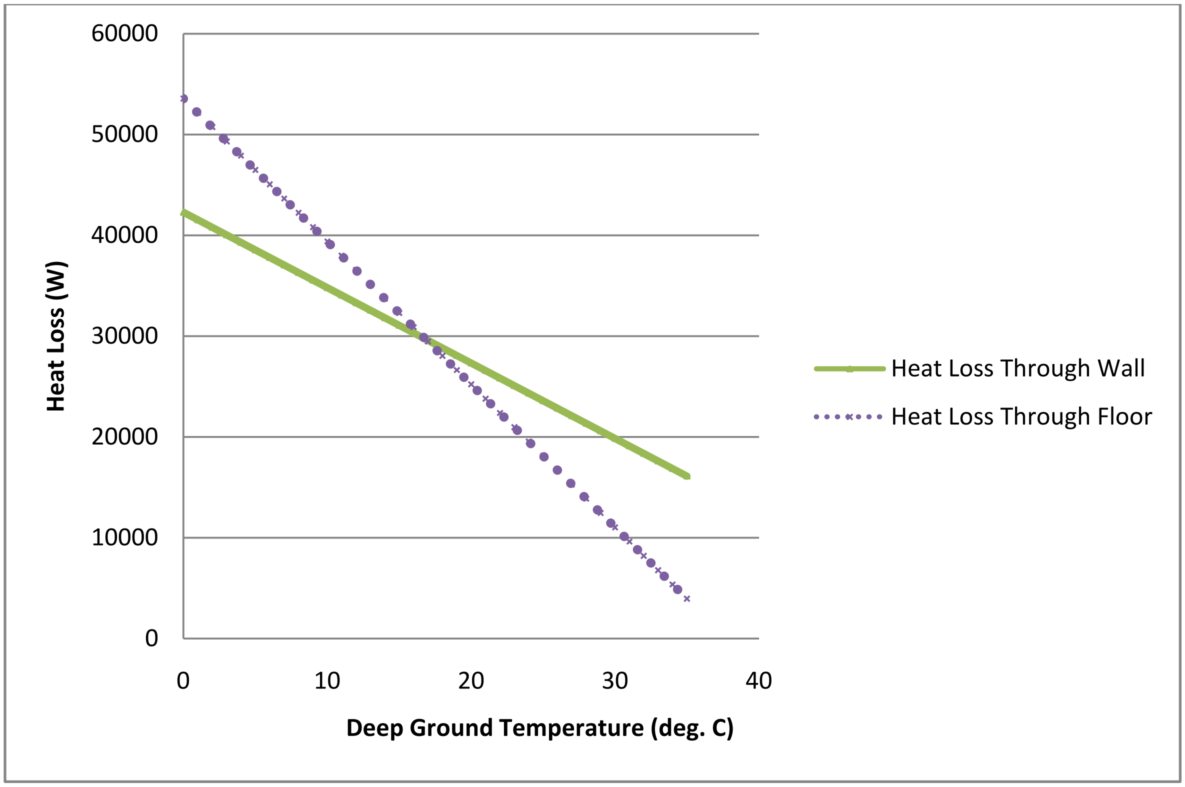

Figure 4.2: Heat loss through the floor and wall (in Watts) at various deep ground temperatures (in Celsius). The reference ambient temperature of 19°C was assumed.

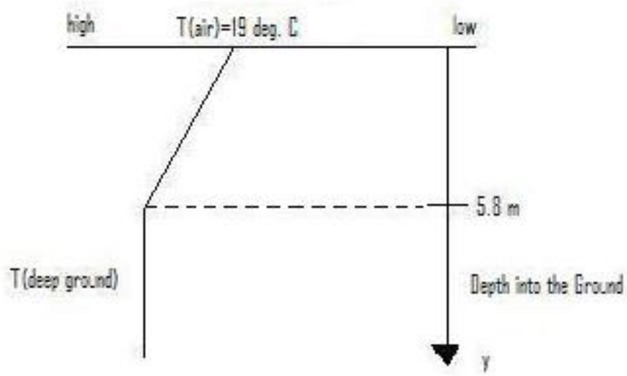

Figure 4.3a: Assumed temperature profile through the ground when deep ground temperature is higher than ambient temperature. The deep ground temperature that is varied in Figure 4.1 is the constant ground temperature beyond the digester depth of 5.8 m.

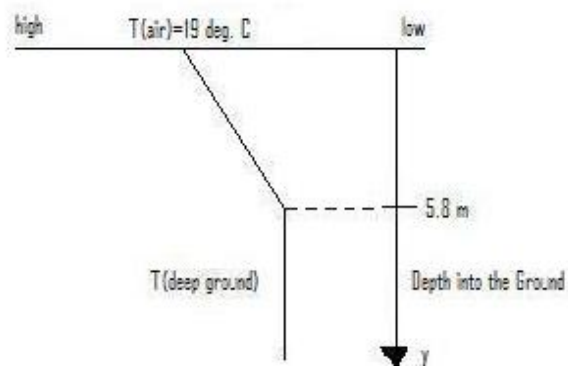

Figure 4.3b: Assumed temperature profile through the ground when the deep ground temperature is lower than ambient temperature.

As can be seen from Figure 4.1, at low deep ground temperatures more heat is lost through the floor than the walls, and the opposite is true at high deep ground temperatures. Using Excel's "Goal Seek" function, equal heat loss through the floor and walls (at $2.97*10^4$ W) was found to occur at 16.83°C. This temperature is lower than the reference ambient temperature of 19°C, because the wall surface area is larger than that of the floor, which makes up for the larger temperature gradient through the floor when the deep ground temperature is 16.83°C and the wall temperature is 17.92°C (the average of 19°C and 16.83°C). Since the model assumes a deep ground temperature which is lower than 16.83°C, more heat is lost through the digester floor than the walls, causing heat requirement to be more sensitive to variations in floor materials compared to wall materials.

4.1.2 Floor, Wall, and Insulation Conductivity

Heat requirement is affected by floor conductivity through Equation 4.2, which calculates the resistance of the floor, and wall conductivity through Equation 4.6, which calculates the resistance of the wall. The conductivity of insulation (of both the floor and walls) is included in both Equation 4.2 and 4.6, so it affects the resistance of the floor and the walls. The model assumes that the same insulation is used for the floor and the walls, so only one set of insulation conductivities were examined.

Simulation Results

The simulated average heat requirement (in Watts) at the high, reference, and low levels of floor, wall, and insulation conductivities were extracted from 54 Excel spreadsheets. These average heat requirement values are given in Table 4.3.

Table 4.3: Simulation results for average heat requirement at the high, reference, and low levels of wall, floor, and insulation conductivity

Average Heat Requirement (Watts) * 10^6									
	Wall Conductivity			Floor Conductivity			Insulation Conductivity		
Variable Value (W/m*k)	2.5	1.5	0.5	2.5	1.5	0.5	0.25	0.15	0.05
Avg. Heat Req.	209	205	195	240	213	156	262	213	133

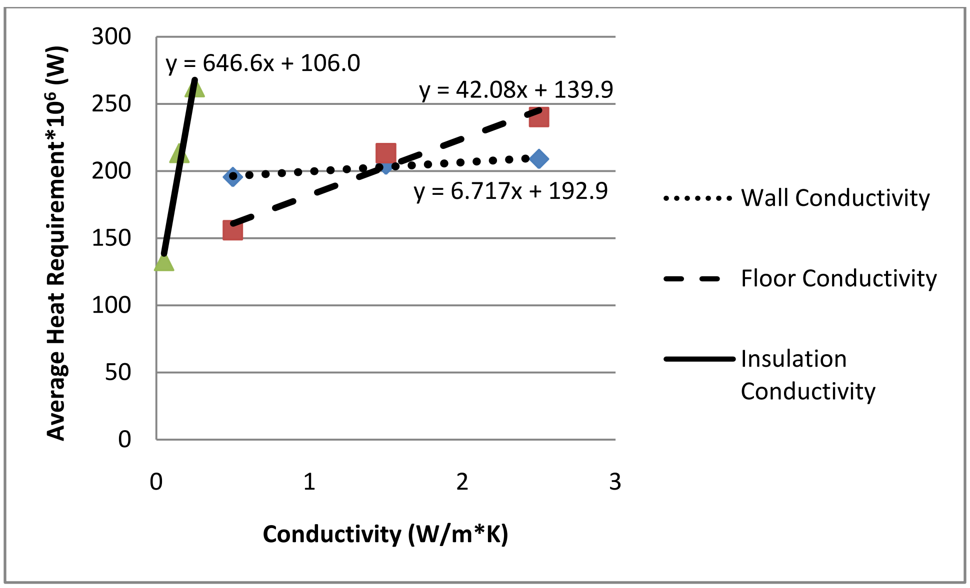

Figure 4.4: Average heat requirement as a function of conductivity of the wall, floor, and insulation.

As shown in Figure 4.4, insulation, floor, and wall conductivities all have a positive relationship with heat requirement. Since conductivity possesses a negative relationship with resistance, all conductivity variables should possess a positive relationship with heat requirement, because higher resistance values lead to less heat loss and requirement.

Also shown in Figure 4.4, heat requirement is the most sensitive to insulation conductivity, second most sensitive to floor conductivity, and least sensitive to wall conductivity. By taking ratios of the slopes of the best-fit lines, insulation conductivity has a much greater effect on heat requirement than floor conductivity (15.37 times) and wall conductivity (96.30 times). These findings are consistent with the results of Section 4.1.1, which report that insulation material is more significant than floor and wall material relative to heat requirement. Furthermore, insulation conductivity affects both wall and floor resistance, while wall and floor conductivities only affect their respective resistances, also increasing the impact of insulation conductivity on heat requirement.

Floor conductivity had the second largest effect on heat requirement, which is also consistent with Section 4.1.1, because floor resistance was shown to have a more significant impact on heat requirement than wall resistance.

4.1.3 Hydraulic Retention Time (HRT):

Hydraulic retention time (HRT) indirectly affects heat requirement through its effect on biogas production. As more influent volatile solids are converted to biogas, there is a decrease of slurry flow out of the digester. This is relevant to heat loss, because less slurry flow out of the digester causes less heat to be carried out by the effluent. The equation for heat loss (in Watts) due to mass flow out of the digester is

$$Q_{manure\ \ out} = (\dot{m}_{manure} - BG) * c_{p_{manure}} * T_0 \qquad (4.8)$$

$\dot{m}_{manure}$ is the manure flow rate (in kg/day) and $c_{p_{manure}}$ is the specific heat of the manure (in kJ/kg*K). T_0 is the operating temperature of the digester, which is constant at 37.78°C. *BG* is the mass of volatile solids that is converted to biogas within the hydraulic retention time (kg/day).

Simulation Results

The average heat requirement values (in Watts) at the high, reference, and low levels of hydraulic retention time were extracted from the 54 Excel spreadsheets. These average heat requirements are displayed in Table 4.4.

Table 4.4: Simulation results for average heat requirement at the high, reference, and low levels of HRT

HRT (days)	Average Heat Requirement (W)*10^6	% Difference from Reference (Heat Req.)
40	217	+3.83%
22	209	-----
8	183	-12.44%

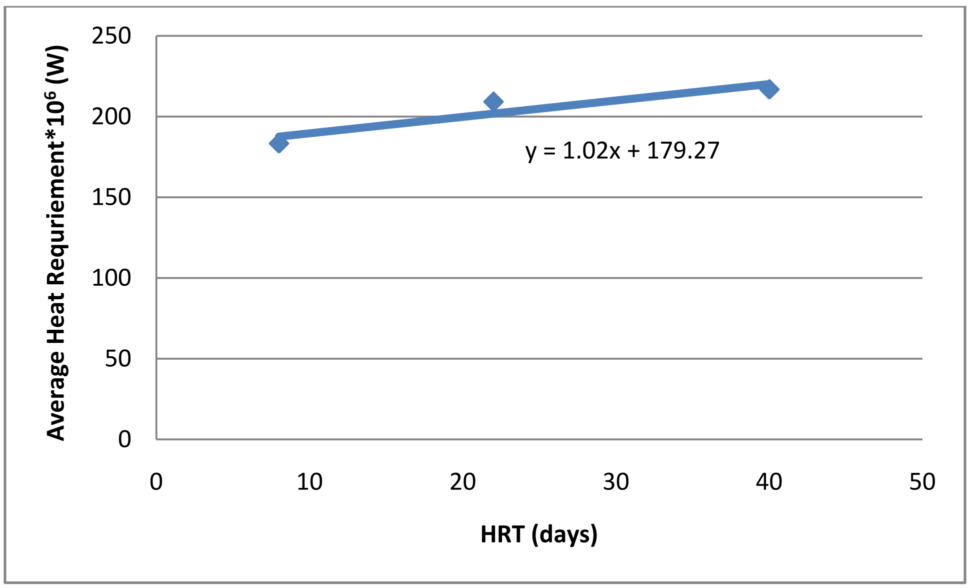

Figure 4.5: Average heat requirement as a function of HRT.

As seen from Figure 4.5, there is a positive relationship between heat requirement and *HRT*. This occurs because an increase in *HRT* causes a decrease in biogas production (See Section 4.2.3), which in turn causes more heat to be carried out of the digester through the effluent slurry. Therefore, as HRT increases, heat loss/requirement also increases.

As seen in Table 4.4 and Figure 4.5, heat requirement rises at a slower rate as *HRT* increases. This trend is consistent with findings in Section 4.2.3, where decreasing *HRT* was found to have an increasing positive impact on biogas production. Since biogas production is subtracted from manure flow rate in Equation 4.8 to determine heat requirement, *HRT* and heat requirement exhibit the opposite relationship as *HRT* and biogas production.

4.1.4 Manure Flow Rate:

Heat loss (or requirement) due to manure flow rate is affected by both the flow of manure into the digester as well as the flow of manure out of the digester. First, heat is required to raise the temperature of the influent manure to the operating temperature, and is calculated as

$$Q_{manure\ \ in} = \dot{m}_{manure}\ c_{p_{manure}}\ (T_0 - T_{manure\ ,in}) \qquad (4.9)$$

$T_{manure\ ,in}$ is the temperature of incoming manure (in Celsius), which is set to the ambient temperature. The other variables are the same as in Equation 4.8.

Heat loss due to manure flow out of the digester is caused by heat being carried out by the effluent slurry since the effluent leaves the digester at the digester operating temperature of 37.78°C. The amount of heat that is lost was calculated using Equation 4.8.

Manure flow rate is also used in Equation 4.17 to calculate biogas production, however the effect of flow rate on biogas production is negligible (see Section 4.2.2).

Simulation Results

The average heat requirement values (in Watts) at the high, reference, and low levels of manure flow rate were extracted from the 54 Excel spreadsheets. These average heat requirements are displayed in Table 4.5.

Table 4.5: Simulation results for average heat requirement at high, reference, and low levels of manure flow rate

Manure Flow Rate (m^3/day)	Average Heat Requirement*10^6 (W)
120 (High)	264
60 (Reference)	186
40 (Low)	159

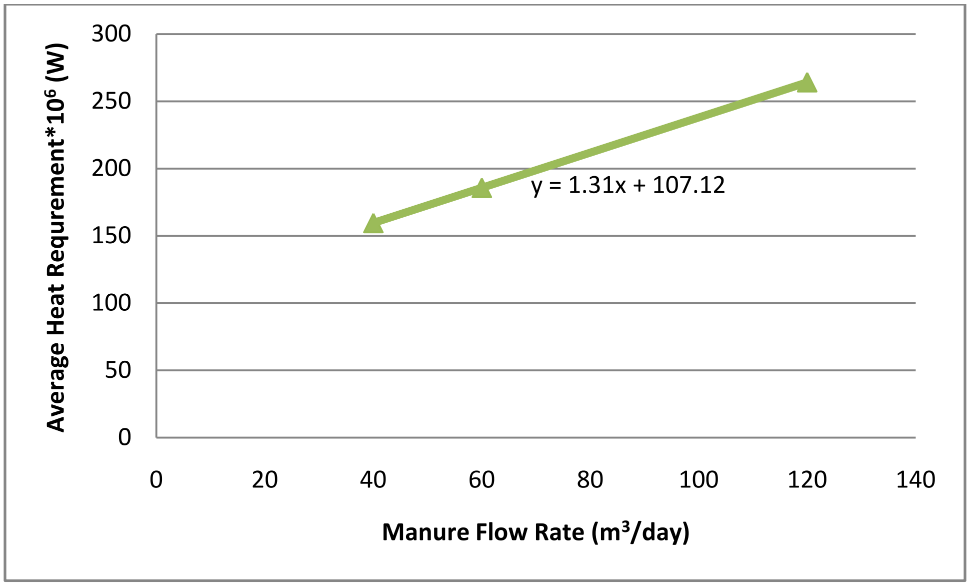

Figure 4.6: Average heat requirement as a function of manure flow rate.

Manure flow rate exhibits a positive relationship with heat requirement. In both Equations 4.8 and 4.9, a higher manure flow rate leads to an increase in heat requirement. With a larger flow rate, there is an increased volume of manure to be heated and, at the same time, heat is being carried out of the digester at a faster rate.

4.1.5 Ambient Temperature:

Ambient temperature influences three aspects of digester heat requirement: heat loss through the digester's walls, heat loss through the digester's cover, and heat required to heat incoming manure to the digester operating temperature. Heat loss through the digester wall is calculated in Section 4.1.1 and heat required to heat incoming manure is calculated in Equation 4.9.

In order to determine heat loss through the digester's cover, first heat flux through the cover is calculated using

$$q''_{cover} = \frac{(T_0 - T_c)}{\sum R_{cover}} \qquad (4.10)$$

T_c represents the temperature at the cover-air interface (in Celsius), and is set to the ambient temperature. q''_{cover} (in W/m^2) is then used to find heat loss through the cover, Q_{cover} (in W), using the equation

$$Q_{cover} = q''_{cover} A_{cover} \qquad (4.11)$$

<u>Simulation Results</u>

The average heat requirement values (in Watts) at the high, reference, and low levels of ambient temperature were extracted from the 54 Excel spreadsheets. These average heat requirements are displayed in Table 4.6.

Table 4.6: Simulation results for average heat requirement at high, reference, and low levels of ambient temperature

Ambient Temperature (°C)	Average Heat Requirement $*10^6$ (W)
30	0.088
19	186
5	423

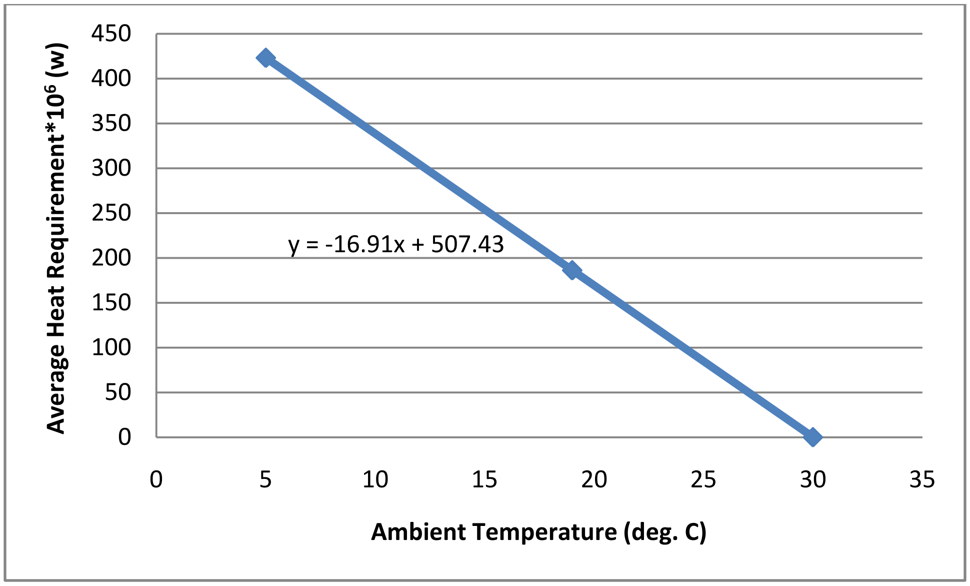

Figure 4.7: Average heat requirement as a function of ambient temperature.

As shown in Figure 4.7, ambient temperature has a negative relationship with heat requirement. This is because ambient temperature shares a negative relationship with all three aspects of heat requirement that it affects: heat loss through the digester's walls, heat loss through the digester's cover, and heat required to heat incoming manure.

As seen in Equation 4.9, an increase in ambient temperature causes a decrease in the heat required to heat incoming manure, because the influent manure's initial temperature is higher. This means less heat needs to be supplied to the influent to raise its temperature to the digester operating temperature.

A higher ambient temperature also causes a higher temperature at the wall-ground interface and the cover-air interface, and results in a smaller temperature gradient through both surfaces. As seen in Equations 4.4 and 4.10, an increase in ambient temperature decreases heat flux through the walls and cover, and causes less heat to be lost through these surfaces. Therefore, an increase in ambient temperature has a negative effect on heat loss (or requirement) through the walls and cover.

4.1.6 Soil Density, Specific Heat, and Conductivity:

Soil properties are taken into account when the top layer of soil is frozen. The depth of frozen soil is calculated using the equation:

$$h_{frozen} = y = \sqrt{\frac{\alpha_{soil}\, t_0}{\pi}} \ln \frac{A_F}{A_y} \qquad (4.12)$$

A_F represents the temperature amplitude at the ground surface and A_y represents the average yearly temperature. t_0 is a measure of time length, which in this case is one year. α_{soil} represents the thermal diffusivity of the soil, which is dependent on the soil density (ρ_{soil}), specific heat ($c_{p\,soil}$) and conductivity (DK_{soil}) by the following relationship:

$$\alpha_{soil} = \frac{DK_{soil}}{\rho_{soil}\, c_{p\,soil}} \qquad (4.13)$$

The thermal diffusivity of the soil (α_{soil}) is also used in the calculation of time lag, which takes into account the lag of ground temperature behind ambient temperature due to the heat-holding capacity of the ground. The following periodic function is used to determine thermal lag time (t_{lag}).

$$\cos\left(\frac{2\pi}{t_0} t_{lag} - \sqrt{\frac{\pi}{\alpha_{soil}\, t_0}} h_{frozen}\right) = 1 \qquad (4.14)$$

These calculations involving frozen ground are irrelevant during times when the ground is not frozen. Since only ambient temperatures of 30°, 19°, and 5° C were inputted into the model, frozen ground was never encountered and heat loss through the floors and walls were estimated using methods described in Section 4.1.1. Therefore, soil density (ρ_{soil}), specific heat ($c_{p\,soil}$) and conductivity (DK_{soil}) were not taken into account in this model.

4.1.7 Radius:

The size of the digester directly determines the surface area of the digester, which affects the area which heat can escape through the cover, floor, and walls. Heat loss through the floor wall and cover are calculated in Equations 4.3, 4.7, and 4.11, respectively.

Digester radius also affects the amount of solar heat gain through the cover. This solar heat gain through the cover is modeled by the equation:

$$Q_{solar} = \bar{q}''_{solar} A_{cover} \tau(\lambda) \qquad (4.15)$$

$\bar{q}''_{solar}$ (in W/m^2) represents the average daytime solar radiation flux, which is estimated based on the latitude and longitude of the location of the digester. $\tau(\lambda)$ is the transmissivity of the covering material (dimensionless), and A_{cover} is the area of the cover of the digester (in m^2).

Simulation Results

Average heat requirement values (in Watts) at the nine different radii were extracted from the 54 Excel spreadsheets. These average heat requirements are displayed in Table 4.7.

Table 4.7: Simulation results for average heat requirement (W) as a function of radii (m), hydraulic retention time (days), and manure flow rate (m^3/day).

Radius (m)	Hydraulic Retention Time (*HRT*)	Manure Flow Rate (*u*)	Average Heat Requirement
m	days	m^3/day	W*10^6
16.23	40	120	278
11.48	40	60	199
2.96	40	40	173
12	22	120	270
8.5	22	60	192
8.51	22	40	165
7.26	8	120	244
5.13	8	60	166
4.19	8	40	140

As shown in Table 4.7, while the nine simulated radii varied between 4.19 to 16.23 m, hydraulic retention time (*HRT*) and manure flow rate (*u*) were also varied between their respective high, low, and reference values. In order to isolate the effect of radius on heat requirement, the data was normalized with respect to *HRT* and *u*.

The first step of normalization was to normalize average heat requirements with respect to *HRT*. The rate of change of *HRT* versus heat requirement ($\frac{\Delta Heat\ Req.}{\Delta HRT}$) was extracted from Section 4.1.3. For the three data points taken at *HRT*'s high values, the this rate of change was multiplied by the value of HRT_{high}-$HRT_{reference}$. The resulting value was then subtracted from the average heat requirement to obtain an equivalent heat requirement value taken at *HRT*'s reference level rather its high level. The equation used was

$$Heat\ Req._{normalized} = Heat\ Req._{simulated} - (HRT_{high} - HRT_{ref})\frac{\Delta Heat\ Req.}{\Delta HRT} \tag{4.16}$$

The average heat requirements taken at *HRT*'s low levels were raised to an equivalent heat requirement taken at *HRT*'s reference level using the same method.

The second step of normalization was to normalize average heat requirements with respect to *u*. The process used was the same as the one used for *HRT*. The rate of change of *HRT* versus heat requirement ($\frac{\Delta Heat\ Req.}{\Delta u}$) was extracted from Section 4.1.4.

<u>Normalized Simulation Results</u>

The normalized average heat requirement values are displayed in Table 4.8, and the normalized heat requirement values were plotted against radius to in Figure 4.8.

Table 4.8: Normalized simulation results for average heat requirement at each digester radius.

Radius (m)	Avg. Heat Req. (W) * 10^6
16.23	199.6978
11.48	181.3256
2.96	175.2015
12	210.1304
8.5	191.6564
8.51	185.4983
7.26	198.3385
5.13	179.7775
4.19	173.5905

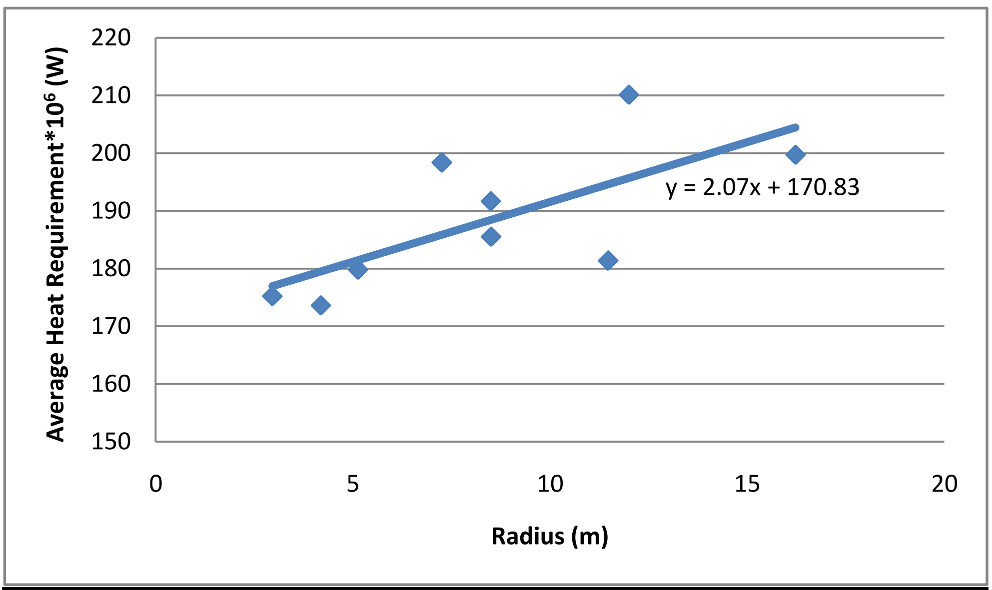

Figure 4.8: Normalized heat requirement (W) as a function of radius (m).

While the data points are scattered around the best-fit line, there is a clear positive correlation between radius and heat requirement. A larger surface area causes more heat loss through the wall, floor, and cover, but on the other hand, it increases the amount of solar heat gain through the cover. However, the high digester operating temperature, which is 18.78°C higher than the reference ambient temperature, induces a large temperature gradient through the walls, floor, and cover, causing the total heat loss to outweigh the solar heat gain. Therefore, an increase in radius brings about an overall rise in heat loss, thus explaining the positive relationship that is shared between radius and heat requirement.

To obtain a better estimate for the trend, it would be useful to test more radii at the same *HRT* and *u* to avoid the need for normalization. If this simulation is conducted, ensure all tank sizes are large enough to accommodate the *HRT* and *u* used.

4.1.8 Overall:

In order to compare the effects of different variables on heat requirement, the overall rates of change for each variable versus heat requirement were sorted from largest to smallest in Table 4.9. These rates of change were taken to be the slope of the best-fit lines that were generated in Sections 4.1.1 through 4.1.7. Values in the "Percent of Total Rate of Change" column were calculated by taking each individual rate of change and dividing it by the sum of all these rates of change.

Table 4.9: Rate of change and percent of total rate of change for each input variable relative to heat requirement

Variable	Overall Rate of Change of Heat Req.*10^6 (W)	Percent of Total Rate of Change (%)
Floor Insulation Thickness (m)	1520	56.62
Insulation Conductivity (W/m*K)	647	24.10
Wall Insulation Thickness (m)	242	9.01
Floor Thickness (m)	175	6.52
Floor Conductivity (W/m*K)	42	1.57
Wall Thickness (m)	28	1.04
Ambient Temperature (deg. C)	17	0.72
Wall Conductivity (W/m*K)	7	0.25
Radius (m)	2	0.08
Manure Flow Rate (m^3/day)	1	0.05
HRT (days)	1	0.04
Soil Density (kg/m^3)	0	0
Soil Specific Heat (kJ/kg*K)	0	0
Soil Conductivity (W/m*K)	0	0

To provide a visual representation for how the input variables rank in their effect on heat requirement, a bar graph was also created in Figure 4.9.

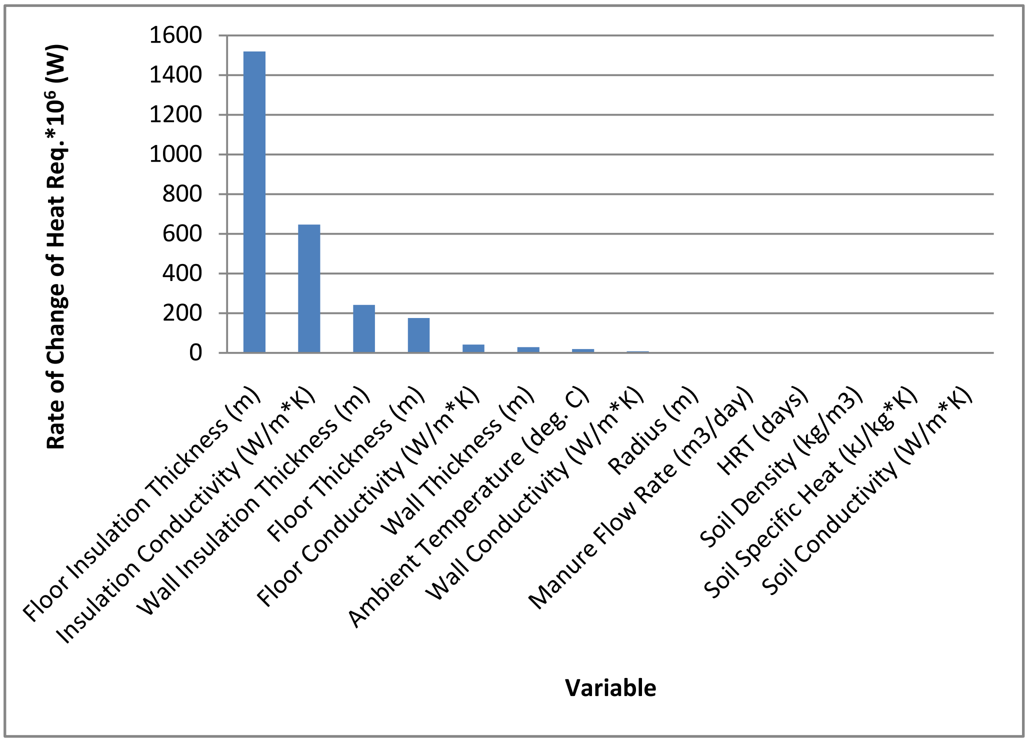

Figure 4.9: Bar graph displaying overall rate of change for each input variable relative to heat requirement

As shown in Figure 4.9, heat requirement changes at the highest rate with floor insulation thickness, followed by insulation conductivity and then wall insulation thickness. The percentage of the total rate of change that these three insulation variables constitute is given in a pie chart (Figure 4.10). In this pie chart, the “Other Building Materials” category consists of floor and wall thicknesses and conductivities, and the “Non-Building Materials” category consists of ambient temperature, radius, manure flow rate, and hydraulic retention time. Since soil density, specific heat, and conductivity were not considered in the model, they were omitted in the analysis.

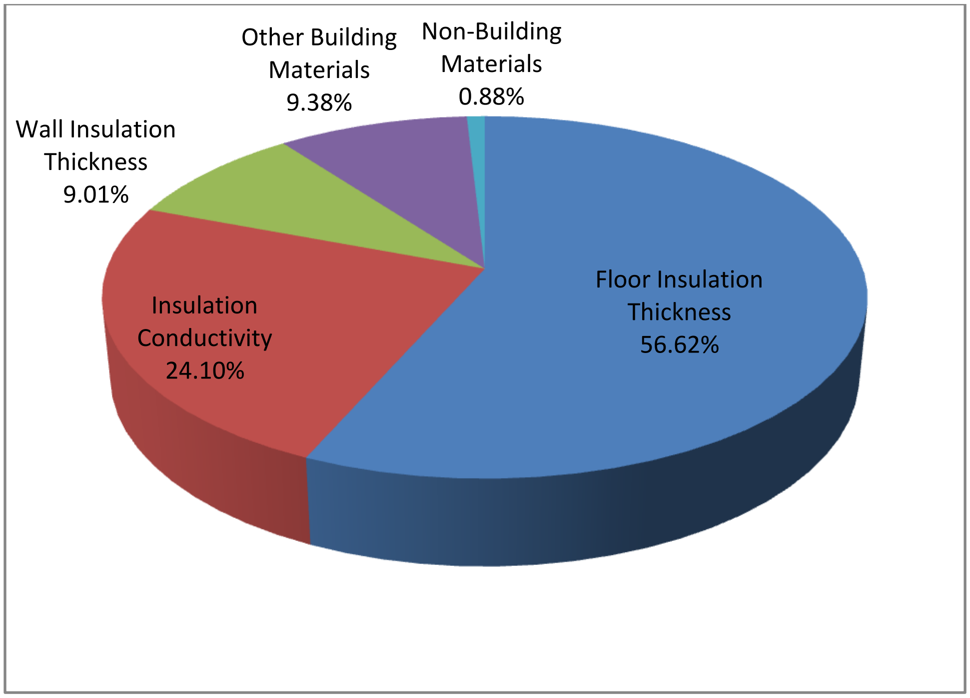

Figure 4.10: Pie chart representing the percent of total rate of change for floor insulation thickness, insulation conductivity, wall insulation thickness, other building materials, and non-building materials.

The combined rates of change or the three insulation variables accounts for 89.73% of the total rate of change. Therefore, out of all the variables taken into account in this model, insulation characteristics are by far the most important factor to consider in estimating heat requirement. This model used a relatively high average ambient temperature compared to the deep ground temperature causing most heat to be lost through the digester floor, so heat requirement was the most sensitive to floor insulation thickness. However, when the ambient temperature is lower compared to the deep ground temperature, more heat will be lost through the walls than the floor (See Section 4.1.1) and heat requirement becomes more sensitive to wall insulation than floor insulation.

It can also be seen from Table 4.9 that out of the eight variables with the highest effect on heat requirement, seven pertained to digester building materials. While insulation is the most important building material to consider, other building materials make up 9.38% of the remaining 10.27% of the total rate of change. This significant percentage means floor and wall thickness and floor and wall conductivity are important in minimizing heat loss.

On the other hand, the effect of non-building materials on heat requirement is insignificant as together they only make up 0.88% of the overall rate of change. Ambient temperature has the seventh highest effect on heat requirement, which is the highest out of all non-building material variables. However, Table 4.9 shows that it only induces 0.72% of the overall influence on heat requirement, so it can be considered negligible. Radius, *HRT*, and manure flow rate have an even lesser effect on heat requirement, and can also be deemed negligible in their effects on heat requirement. Since it is not crucial to consider the impact of these variables on heat requirement, these variables should be manipulated to increase biogas production rather than decrease heat loss.

Soil density, specific heat, and conductivity have no effect on heat requirement in this case, because the ground is never frozen. However, a model incorporating frozen ground should be simulated to determine the potential effects of soil properties.

<u>Eliminating the Effects of Trends</u>

Since not all variables produced a linear trend through the three levels tested, the maximum and minimum rates of change (versus heat requirement) for each variable were compared. The maximum rate of change was found by comparing the rates of change between the low and reference points and the high and reference points, and selecting the highest rate of change. Conversely, the minimum rate of change was chosen to be the smaller of the two rates of change. By comparing each variable's maximum and minimum rates of change, the potential (rather than the average) effects of each input variable can be determined.

Table 4.10: Maximum and minimum rate of change for each of the input variables. The input variables that could potentially be switched in ranking based on significance on heat requirement are highlighted.

Variable	Absolute Rate of Change of Heat Req.*10^6 W (Low to Reference)	Absolute Rate of Change of Heat Req.*10^6 W (High to Reference)	Maximum Rate of Change	Minimum Rate of Change
Floor Insulation Thickness (m)	1920	1110	1920	1110
Insulation Conductivity (W/m*K)	804	490	804	490
Wall Insulation Thickness (m)	306	178	306	178
Floor Thickness (m)	205	146	205	146
Floor Conductivity (W/m*K)	57	27	57	27
Wall Thickness (m)	32	23	32	23
Ambient Temperature (deg. C)	9	9	9	9
Wall Conductivity (W/m*K)	9	4	9	4
Radius (m)	2	2	2	2
Manure Flow Rate (m^3/day)	2	0	2	0
HRT (days)	1	1	1	1
Soil Density (kg/m^3)	0	0	0	0
Soil Specific Heat (kJ/kg*K)	0	0	0	0
Soil Conductivity (W/m*K)	0	0	0	0

To providea visual representation for how each input variable differs in their maximum and minimum effect on heat requirement, a clustered bar graph (Figure 4.11) was also created. The bar graph also enables the comparison of maximum and minimum rates of change for different variables.

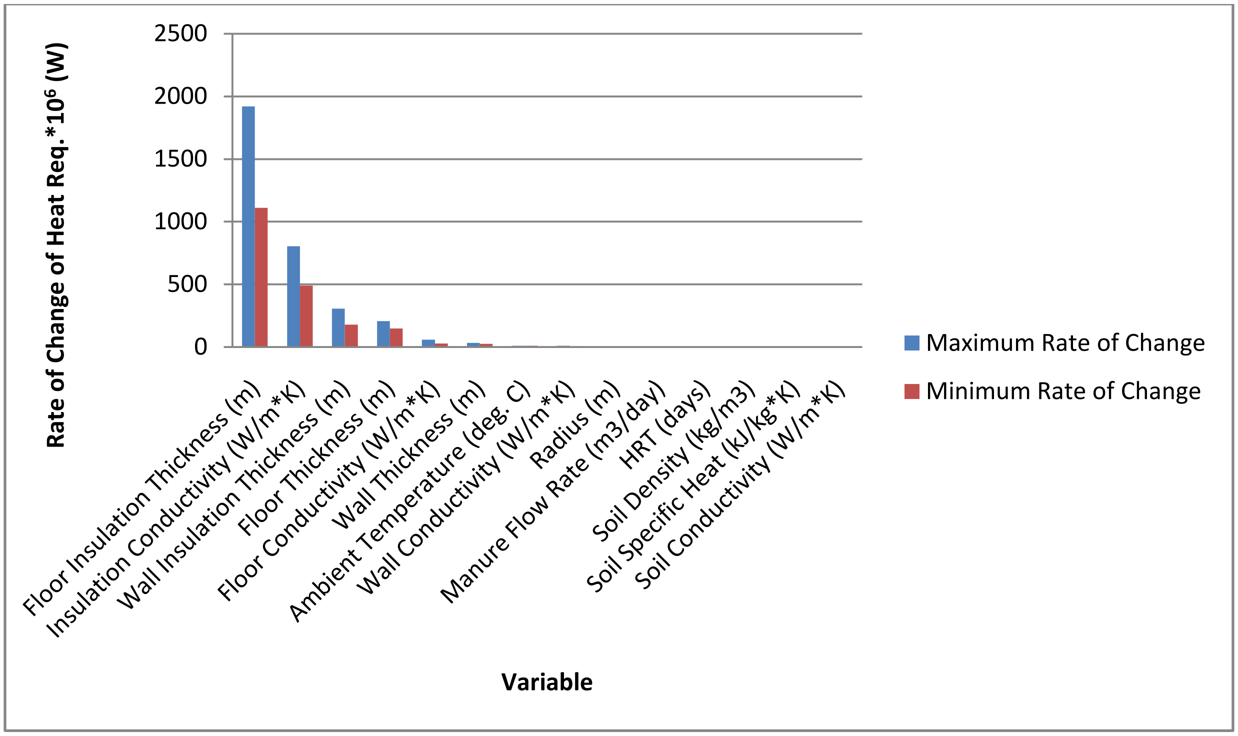

Figure 4.11: Clustered bar graph showing the maximum and minimum rate of change for each of the input variables

As can be seen from Table 4.10, the significant variables rank in the same order when separately considering the maximum and minimum rate of change relative to heat requirement. However, the maximum rate of change for floor thickness is larger than the minimum rate of change for wall insulation thickness and the maximum rate of change for wall thickness is larger than the minimum rate of change for floor conductivity. Therefore, if wall insulation or floor conductivity are at high values, causing less of an effect on heat requirement (See Table 4.10), and floor thickness and wall thickness are at lower values, causing a larger effect on heat requirement, then both the latter variables can potentially have a greater effect on heat requirement than the two prior variables. However, these differences that occur are not significant, and do not drastically influence design priorities. Furthermore, since these variables have a significant effect on heat loss, material conductivities will be kept at lower values and material thicknesses at higher values. Therefore, a design with high material conductivities and low thicknesses will not likely be encountered, which means priorities would stay constant.

4.2 Effects on Biogas Production

The amount of biogas production was calculated using the model developed by Minott (2002) and is expressed as:

$$BG = \frac{b}{HRT} * [C_0 - C_T(x,t)] * V * \frac{T_a}{T_o} \qquad (4.16)$$

BG represents the amount of biogas that is produced in one day (m^3/day) and b represents the amount of biogas that is produced per weight of volatile solid destroyed (m^3/kg). HRT stands for the hydraulic retention time (days) and V the volume of the digester (m^3). T_a is the ambient temperature (K) and T_o is the temperature of the manure in the digester (K). C_0 is the total amount of volatile solids flowing into the digester (kg/m^3) and $C_T(x,t)$ is the total substrate degradation in the digester (kg/m^3). $C_T(x,t)$ was calculated using the equation presented in Minott (2002):

$$C_T(x,t) = \frac{C_0 * k * e^{\left(-\frac{1}{k}\right)}}{\mu_m^2 * V * HRT}\{(V * \mu_m - 2u * k)\left[1 - e^{\left(-\mu_m * \frac{HRT}{k}\right)}\right] + HRT * u * \mu_m \left[1 + e^{\left(-\mu_m * \frac{HRT}{k}\right)}\right]\}$$

(4.17)

k represents the kinetic parameter (dimensionless) and is calculated using the experimentally-determined equation given in Hashimoto (1984): $k = 0.6 + 0.0206 * e^{(0.051 * S_0)}$, where S_0 is the concentration of volatile solids in the influent. μ_m represents the growth rate per day (day^{-1}) and is calculated using the following equation given in Hashimoto et al. (1981): $\mu_m = 0.013 * T_0 - 0.129$, where T_0 is the manure temperature (°C). In this case, $T_0 = 37.8$°C. u is the daily flow rate of the manure into the digester (m^3/day).

The values of these variables used in the model are displayed in Table 4.11.

Table 4.11: Input variables values that are used in Equations 4.16 and 4.17 in the model

Equation 4.16 Variables	Units	Value
B	m^3/kg	0.5
HRT	Days	8 (Low), 22 (Reference), 40 (High)
V	m^3	F(Digester dimensions)
T_a	K	273.2
T_0	K	311
C_0	kg/m^3	75.59
Equation 4.17 Variables	**Units**	**Value**
K	Dimensionless	1.26
μ_m	day^{-1}	0.3624
U	m^3/day	40 (Low), 60 (Reference), 120 (High)

4.2.1 Simulation Results:

In the simulation, both hydraulic retention time (*HRT*) and daily flow rate (*u*) were varied between high, reference, and low values (as seen in Table 3.1). Table 4.12 below displays the rate of biogas production (m^3/day) at each combination of *HRT* and *u*. By taking the average biogas production at each level of *HRT* and *u*, the effect of each variable on biogas production was determined.

Table 4.12: Average rate of biogas production for each level of *u* and *HRT*.

Biogas Production*10^5 (m^3/day)					
	Flow Rate (m^3/day)				
HRT (days)	**120**	**60**	**40**	**Average**	**% Difference from Reference**
40	35.1	35.8	36.0	**35.6**	**43.40%**
22	62.0	63.1	63.4	**62.9**	**-----**
8	154	155	156	**155**	**146.42%**
Average	**83.7**	**84.6**	**85.1**		

The rate of biogas production at the nine combinations of *HRT* and *u* were graphed in Figure 4.12. To visualize the effect of *HRT* on biogas production, *HRT* was plotted on the X-axis. To visualize the effects of *u* on biogas production, three different trend lines were created to represent the high, reference, and low levels of *u*.

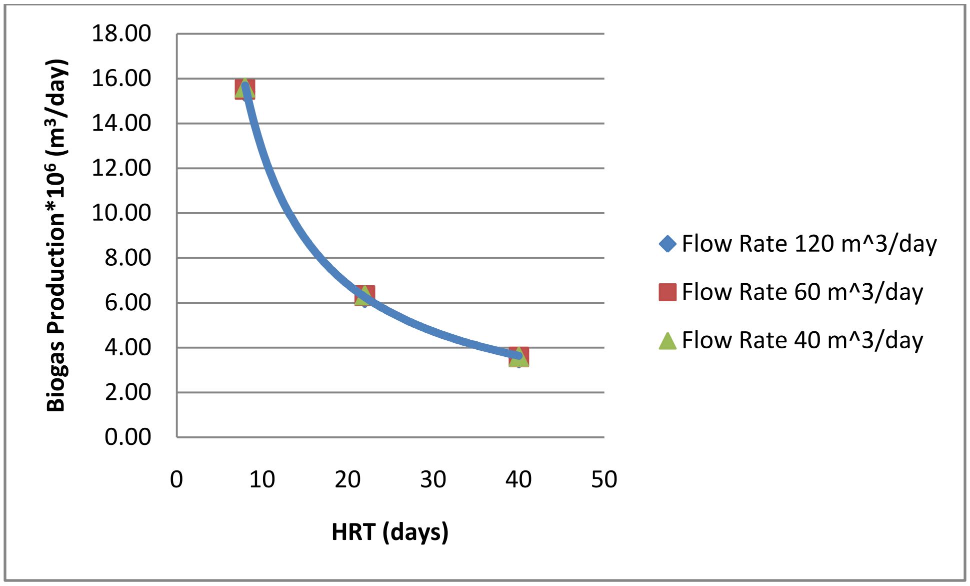

Figure 4.12: Rate of biogas production as a function of HRT. Three different trend lines were created to represent the low, reference, and high flow rates.

4.2.2 Manure Flow Rate (*u*) versus Biogas Production:

As shown in Figure 4.12, the trend lines for the high, reference, and low values of flow rate (*u*) are virtually overlapping. Therefore, at each *HRT*, variations in *u* caused very little variation in biogas production. Since *HRT* has a significant negative effect on biogas production as seen in Figure 4.12, *u* has a negligible effect on biogas production relative to *HRT*. As seen in Table 4.12, the average biogas production does remains nearly constant as *u* is varied.

To verify the simulation results, biogas production values at the high, reference, and low *u* values were manually calculated. These calculations were carried out using Equations 4.16 and 4.17. The constants that were inputted into these equations are displayed in Table 4.11. The reference *HRT* value (22 days), and a volume of 4386.25 m^3 (calculated using the default rectangular dimensions of 55m*13.75m*5.8m) were also used in the calculations.

Table 4.13: Manually calculated rates of biogas production at the high, reference, and low manure flow rates (*u*)

Flow Rate (*u*)	$C_T(x,t)$	*BG*
120 (High)	7.62	5951.90
60 (Reference)	6.51	6049.60
40 (Low)	6.14	6082.17

u's negligible effect on biogas production can be explained using Equations 4.16 and 4.17, which are used to calculate biogas production. *u* only appears in Equation 4.17 meaning that it only affects biogas production by affecting the value of $C_T(x,t)$. As seen in Table 4.12 and 4.13, $C_T(x,t)$ is hardly affected by varying *u*. Since this is *u*'s lone effect on biogas production, *u* only causes a very slight effect on overall biogas production. Based on the extremely small variations in biogas production at the high, reference, and low levels of *u*, it can be concluded that *u* has a negligible effect on biogas production in this model.

4.2.3 Hydraulic Retention Time (*HRT*) versus Biogas Production:

Contrary to flow rate, *HRT* possesses a significant negative relationship with biogas production, meaning the rate of biogas production increases as *HRT* decreases. In addition, this increase in biogas production appears exponential. This is confirmed in Table 4.12, where there is a much larger percent difference between the low and reference *HRT* (146.42%) than the high and reference *HRT* (43.40%).

HRT is found in both Equations 4.16 and 4.17, so *HRT* affects $C_T(x,t)$ (through Equations 4.17) and biogas production directly (through Equation 4.16). To verify *HRT*'s overall effect on biogas production, Table 4.14 was created using the same method as Table 4.13, except *HRT* rather than *u* values were varied.

Table 4.14: Manually calculated biogas production at the high, reference, and low *HRT*'s

Hydraulic Retention Time (*HRT*)	***C_T(x,t)***	***BG***	**% Difference at reference level (*BG*)**
40 (High)	4.31	3432.94	43.25%
22 (Reference)	6.51	6049.60	------
8 (Low)	13.88	14,860.02	145.64%

Solely considering *HRT*'s effect on $C_T(x,t)$ (See Table 4.15), it is clear that *HRT* has a larger impact on $C_T(x,t)$ than *u* (See Table 4.13). This implies that *HRT* already has a larger impact on biogas production than *u*.

More significantly, *HRT* has a second effect on biogas production by being directly included in the denominator of Equation 4.16, which was used to calculate biogas production. HRT's influence on biogas production through Equation 4.16 is significantly larger than its influence through Equation 4.17 (which calculates $C_T(x,t)$). Since *HRT* is included in denominator of Equation 4.16, it makes sense that larger values of *HRT* result in smaller values of biogas production. *HRT*'s inclusion in Equation 4.16's denominator also explains the rate of change increase as *HRT* is decreased.

4.2.4 Overall:

In the model, hydraulic retention time, rather than manure flow rate, is the limiting factor in the scenarios simulated. Since manure is flowing in at a steady speed, biogas production must be limited by the amount of time it takes the bacteria to break down the volatile solids, not by the amount of volatile solids constantly flowing into the digester. Furthermore, since the percentage of volatile solids in the manure goes down the longer manure is held in the digester, conversion of these solids into biogas becomes slower with increased time inside the digester. This decrease in rate of volatile solids breakdown explains the negative exponential relationship exhibited in Figure 4.12 between hydraulic retention time and rate of biogas production.

Given a sufficient flow rate and digester size, it is important to find an optimum hydraulic retention time. Although efficiency of biogas production increases as hydraulic retention time decreases, the amount of volatile solids that are wasted rises. Therefore, the rate of biogas production needs to be balanced with the amount of volatile solids wasted in order to find an optimal hydraulic retention time.

5. CONCLUSION

Heat Requirement

1) Heat requirement is mostly affected by insulation. Of the total rate of change, 56.6% is due to insulation thickness, 24% is due to insulation conductivity and 9% is due to wall insulation thickness.
2) Other digester building material properties [floor thickness (6.52%), floor conductivity (1.57%), wall thickness (1.04%), and wall conductivity (0.25%)] accounted for 9.38% of the remaining 10.27% of the total rate of change. Although heat requirement was more sensitive to floor properties than wall properties in this model, the opposite is true when ambient temperature is low compared to deep ground temperature.
3) The following input variables have a negligible effect on heat requirement, together making up merely 0.88% of the total absolute rate of change with respect to heat requirement: ambient temperature (0.72%), hydraulic retention time (0.04%), manure flow rate (0.05%), and digester radius (0.08%). Therefore, hydraulic retention time, manure flow rate, and digester radius should be manipulated to maximize biogas production and minimize cost.
4) Soil specific heat, soil density, and soil conductivity were never employed in calculating heat loss, since the ground was never frozen in this model.
5) On average, more heat was lost through the floor than through the walls of the digester, because ambient temperature was high compared to the constant deep ground temperature. Therefore, while operating the digester on hot days, floor characteristics (insulation, thickness, conductivity) are more critical than wall characteristics.

Biogas Production

1) Hydraulic retention time exhibited a negative exponential relationship with biogas production, i.e., biogas production rose increasingly fast as *HRT* decreased. Biogas production increased by 43% when HRT decreased from 40 to 22 days, and increased by 146% when HRT decreased from 22 to 8 days.

2) Manure flow rate had a negligible effect on biogas production for a flow rate range between 40 and 120 m^3/day.

6. FUTURE WORK

1) The results of this parametric study should be combined with a cost model for each input parameter to determine financially-optimal values for each variable. By directly comparing rates of change, as was done in this study, only rough relationships between input variables can be obtained. Furthermore, in implementing such a method, choice of units can alter sensitivity results.
2) Studies should be conducted at colder ambient temperatures relative to the deep ground temperature to simulate winter conditions. This may induce a partially frozen ground, which would reveal the potential effects of soil properties on heat requirement.
3) For each input variable, a wider range of values need to be evaluated to better estimate the relationships against heat requirement. In this study, a linear relationship was assumed between input variables and heat requirement. By conducting a more extensive simulation, errors based on this assumption can be minimized.
4) The relationship between manure flow rate and biogas production should be verified.
5) Different digester geometries should be studied. In this study, only cylindrical digesters were considered.
6) Digesters built above grade, partially below grade, and completely below grade should be examined. In this study, only a digester that was built completely below grade was considered.

7. References

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8. Appendix, VBA Computer Code

```
' Calculate # observations and heat requirement average
' for each group (High, Reference, Low)
' for the following variables: T_m6, HRT, Flow_m, Thick_w,
' Thick_f, Thick_win, Thick_fin, DK_wall, DK_f, DEN_soil, CP_soil, DK_soil
'
' Also calculated the # observations and heat requirement averages for the 9 different
' Radius sizes and Constant Rectangular size that corresponds to the 9 different
' HRT and Flow_m combinations.

Sub CalculateResults()
    ' ***************************T_m6, Column 1**************************************
    ' Variables to keep track of average heat requirement
    Dim Temp_H_ave, Temp_M_ave, Temp_L_ave As Double
    Temp_H_ave = 0
    Temp_M_ave = 0
    Temp_L_ave = 0

    ' Variables to count # of data points in high, medium (or reference), and low groups
    Dim Temp_H_count, Temp_M_count, Temp_L_count As Long
    Temp_H_count = 0
    Temp_M_count = 0
    Temp_L_count = 0

    ' For loop counter
    Dim i As Long
```

```
' Cycle through each row of data starting from row 3
For i = 2 To 60000
  ' Check if data point is in high group
  If Worksheets("digester_output_part_2").Cells(i, 1).Value = 86 Then
    Temp_H_count = Temp_H_count + 1 ' add 1 to high group's count
    ' calculate high group's average
    Temp_H_ave = (Temp_H_ave * (Temp_H_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / Temp_H_count
  ' Check if data point is in medium group
  ElseIf Worksheets("digester_output_part_2").Cells(i, 1).Value = 66.2 Then
    Temp_M_count = Temp_M_count + 1 ' add 1 to medium group's count
    ' calculate medium group's average
    Temp_M_ave = (Temp_M_ave * (Temp_M_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / Temp_M_count
  ' Data point must be in low group
  Else
    Temp_L_count = Temp_L_count + 1 ' add 1 to low group's count
    ' calculate low group's average
    Temp_L_ave = (Temp_L_ave * (Temp_L_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / Temp_L_count
  End If
Next

' ***************************HRT, Column 2**************************************
' Variables to keep track of average heat requirement
Dim HRT_H_ave, HRT_M_ave, HRT_L_ave As Double
HRT_H_ave = 0
HRT_M_ave = 0
```

```
HRT_L_ave = 0

' Variables to count # of data points in high, medium (or reference), and low groups
Dim HRT_H_count, HRT_M_count, HRT_L_count As Long
HRT_H_count = 0
HRT_M_count = 0
HRT_L_count = 0

' Cycle through each row of data starting from row 3
For i = 2 To 60000
  ' Check if data point is in high group
  If Worksheets("digester_output_part_2").Cells(i, 2).Value = 40 Then
    HRT_H_count = HRT_H_count + 1 ' add 1 to high group's count
    ' calculate high group's average
    HRT_H_ave = (HRT_H_ave * (HRT_H_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / HRT_H_count
  ' Check if data point is in medium group
  ElseIf Worksheets("digester_output_part_2").Cells(i, 2).Value = 22 Then
    HRT_M_count = HRT_M_count + 1 ' add 1 to medium group's count
    ' calculate medium group's average
    HRT_M_ave = (HRT_M_ave * (HRT_M_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / HRT_M_count
  ' Data point must be in low group
  Else
    HRT_L_count = HRT_L_count + 1 ' add 1 to low group's count
    ' calculate low group's average
    HRT_L_ave = (HRT_L_ave * (HRT_L_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / HRT_L_count
```

```
    End If
Next

' **************************Flow_m, Column 3*************************************
' Variables to keep track of average heat requirement
Dim FlowM_H_ave, FlowM_M_ave, FlowM_L_ave As Double
FlowM_H_ave = 0
FlowM_M_ave = 0
FlowM_L_ave = 0

' Variables to count # of data points in high, medium (or reference), and low groups
Dim FlowM_H_count, FlowM_M_count, FlowM_L_count As Long
FlowM_H_count = 0
FlowM_M_count = 0
FlowM_L_count = 0

' Cycle through each row of data starting from row 3
For i = 2 To 60000
    ' Check if data point is in high group
    If Worksheets("digester_output_part_2").Cells(i, 3).Value = 120 Then
        FlowM_H_count = FlowM_H_count + 1 ' add 1 to high group's count
        ' calculate high group's average
        FlowM_H_ave = (FlowM_H_ave * (FlowM_H_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / FlowM_H_count
    ' Check if data point is in medium group
    ElseIf Worksheets("digester_output_part_2").Cells(i, 3).Value = 60 Then
        FlowM_M_count = FlowM_M_count + 1 ' add 1 to medium group's count
        ' calculate medium group's average
```

```
    FlowM_M_ave = (FlowM_M_ave * (FlowM_M_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / FlowM_M_count
  ' Data point must be in low group
  Else
    FlowM_L_count = FlowM_L_count + 1 ' add 1 to low group's count
    ' calculate low group's average
    FlowM_L_ave = (FlowM_L_ave * (FlowM_L_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / FlowM_L_count
  End If
Next

' *****************************Radi, Column 6*****************************************
' Variables to keep track of average heat requirement
Dim Radi_16_23_ave, Radi_12_ave, Radi_11_48_ave, Radi_8_51_ave, Radi_8_5_ave, _
  Radi_7_26_ave, Radi_5_13_ave, Radi_4_19_ave, Radi_2_96_ave, Rect_16_23_ave, _
  Rect_12_ave, Rect_11_48_ave, Rect_8_51_ave, Rect_8_5_ave, _
  Rect_7_26_ave, Rect_5_13_ave, Rect_4_19_ave, Rect_2_96_ave As Double
Radi_16_23_ave = 0 ' Set Round averages to 0
Radi_12_ave = 0
Radi_11_48_ave = 0
Radi_8_51_ave = 0
Radi_8_5_ave = 0
Radi_7_26_ave = 0
Radi_5_13_ave = 0
Radi_4_19_ave = 0
Radi_2_96_ave = 0
Rect_16_23_ave = 0 ' Set Rectangular averages to 0
Rect_12_ave = 0
```

```
Rect_11_48_ave = 0

Rect_8_51_ave = 0

Rect_8_5_ave = 0

Rect_7_26_ave = 0

Rect_5_13_ave = 0

Rect_4_19_ave = 0

Rect_2_96_ave = 0


' Variables to count # of data points in high, medium (or reference), and low groups

Dim Radi_16_23_count, Radi_12_count, Radi_11_48_count, Radi_8_51_count, Radi_8_5_count, _

   Radi_7_26_count, Radi_5_13_count, Radi_4_19_count, Radi_2_96_count, _

   Rect_16_23_count, Rect_12_count, Rect_11_48_count, Rect_8_51_count, Rect_8_5_count, _

   Rect_7_26_count, Rect_5_13_count, Rect_4_19_count, Rect_2_96_count As Long

Radi_16_23_count = 0 ' Set Round counts to 0

Radi_12_count = 0

Radi_11_48_count = 0

Radi_8_51_count = 0

Radi_8_5_count = 0

Radi_7_26_count = 0

Radi_5_13_count = 0

Radi_4_19_count = 0

Radi_2_96_count = 0

Rect_16_23_count = 0 ' Set Rectangular counts to 0

Rect_12_count = 0

Rect_11_48_count = 0

Rect_8_51_count = 0

Rect_8_5_count = 0

Rect_7_26_count = 0
```

```
Rect_5_13_count = 0
Rect_4_19_count = 0
Rect_2_96_count = 0

' Cycle through each row of data starting from row 3
For i = 2 To 60000
  ' Check if data point has 0 radius, which implies rectangular digest
  If Worksheets("digester_output_part_2").Cells(i, 6).Value = 0 Then
    ' Check if Flow_m equals 40
    If Worksheets("digester_output_part_2").Cells(i, 2).Value = 40 Then
      ' Check if data point is in Rect 16.23 group
      If Worksheets("digester_output_part_2").Cells(i, 3).Value = 120 Then
        Rect_16_23_count = Rect_16_23_count + 1 ' add 1 to Rect 16.23 group's count
        ' calculate Rect 16.23 group's average
        Rect_16_23_ave = (Rect_16_23_ave * (Rect_16_23_count - 1) + _
          Worksheets("digester_output_part_2").Cells(i, 18).Value) / Rect_16_23_count
      ' Check if data point is in Rect 11.48 group
      ElseIf Worksheets("digester_output_part_2").Cells(i, 3).Value = 60 Then
        Rect_11_48_count = Rect_11_48_count + 1 ' add 1 to Rect 11.48 group's count
        ' calculate Rect 11.48 group's average
        Rect_11_48_ave = (Rect_11_48_ave * (Rect_11_48_count - 1) + _
          Worksheets("digester_output_part_2").Cells(i, 18).Value) / Rect_11_48_count
      ' Data point must be in Rect 2.96 group
      Else
        Rect_2_96_count = Rect_2_96_count + 1 ' add 1 to Rect 2.96 group's count
        ' calculate Rect 2.96 group's average
        Rect_2_96_ave = (Rect_2_96_ave * (Rect_2_96_count - 1) + _
          Worksheets("digester_output_part_2").Cells(i, 18).Value) / Rect_2_96_count
```

```
    End If
' Check if Flow_m equals 22
ElseIf Worksheets("digester_output_part_2").Cells(i, 2).Value = 22 Then
    ' Check if data point is in Rect 12 group
    If Worksheets("digester_output_part_2").Cells(i, 3).Value = 120 Then
        Rect_12_count = Rect_12_count + 1 ' add 1 to Rect 12 group's count
        ' calculate Rect 12 group's average
        Rect_12_ave = (Rect_12_ave * (Rect_12_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / Rect_12_count
    ' Check if data point is in Rect 8.5 group
    ElseIf Worksheets("digester_output_part_2").Cells(i, 3).Value = 60 Then
        Rect_8_5_count = Rect_8_5_count + 1 ' add 1 to Rect 8.5 group's count
        ' calculate Rect 8.5 group's average
        Rect_8_5_ave = (Rect_8_5_ave * (Rect_8_5_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / Rect_8_5_count
    ' Data point must be in Rect 8.51 group
    Else
        Rect_8_51_count = Rect_8_51_count + 1 ' add 1 to Rect 8.51 group's count
        ' calculate Rect 8.51 group's average
        Rect_8_51_ave = (Rect_8_51_ave * (Rect_8_51_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / Rect_8_51_count
    End If
' Flow rate must equal 8
Else
    ' Check if data point is in Rect 7.26 group
    If Worksheets("digester_output_part_2").Cells(i, 3).Value = 120 Then
        Rect_7_26_count = Rect_7_26_count + 1 ' add 1 to Rect 7.26 group's count
        ' calculate Rect 7.26 group's average
```

```
            Rect_7_26_ave = (Rect_7_26_ave * (Rect_7_26_count - 1) + _
                Worksheets("digester_output_part_2").Cells(i, 18).Value) / Rect_7_26_count
        ' Check if data point is in Rect 5.13 group
        ElseIf Worksheets("digester_output_part_2").Cells(i, 3).Value = 60 Then
            Rect_5_13_count = Rect_5_13_count + 1 ' add 1 to Rect 5.13 group's count
            ' calculate Rect 5.13 group's average
            Rect_5_13_ave = (Rect_5_13_ave * (Rect_5_13_count - 1) + _
                Worksheets("digester_output_part_2").Cells(i, 18).Value) / Rect_5_13_count
        ' Data point must be in Rect 4.19 group
        Else
            Rect_4_19_count = Rect_4_19_count + 1 ' add 1 to Rect 4.19 group's count
            ' calculate Rect 4.19 group's average
            Rect_4_19_ave = (Rect_4_19_ave * (Rect_4_19_count - 1) + _
                Worksheets("digester_output_part_2").Cells(i, 18).Value) / Rect_4_19_count
        End If
    End If

' If reaches here means digester is round
' So find how large the radius of the digester is:
    ' Check if data point is in Radius 16.23 group
    ElseIf Worksheets("digester_output_part_2").Cells(i, 6).Value = 16.23 Then
        Radi_16_23_count = Radi_16_23_count + 1 ' add 1 to Radius 16.23 group's count
        ' calculate Radius 16.23 group's average
        Radi_16_23_ave = (Radi_16_23_ave * (Radi_16_23_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / Radi_16_23_count
    ' Check if data point is in Radius 12 group
    ElseIf Worksheets("digester_output_part_2").Cells(i, 6).Value = 12 Then
        Radi_12_count = Radi_12_count + 1 ' add 1 to Radius 12 group's count
```

```
    ' calculate Radius 12 group's average
    Radi_12_ave = (Radi_12_ave * (Radi_12_count - 1) + _
        Worksheets("digester_output_part_2").Cells(i, 18).Value) / Radi_12_count
' Check if data point is in Radius 11.48 group
ElseIf Worksheets("digester_output_part_2").Cells(i, 6).Value = 11.48 Then
    Radi_11_48_count = Radi_11_48_count + 1 ' add 1 to Radius 11.48 group's count
    ' calculate Radius 11.48 group's average
    Radi_11_48_ave = (Radi_11_48_ave * (Radi_11_48_count - 1) + _
        Worksheets("digester_output_part_2").Cells(i, 18).Value) / Radi_11_48_count
' Check if data point is in Radius 8.51 group
ElseIf Worksheets("digester_output_part_2").Cells(i, 6).Value = 8.51 Then
    Radi_8_51_count = Radi_8_51_count + 1 ' add 1 to Radius 8.51 group's count
    ' calculate Radius 8.51 group's average
    Radi_8_51_ave = (Radi_8_51_ave * (Radi_8_51_count - 1) + _
        Worksheets("digester_output_part_2").Cells(i, 18).Value) / Radi_8_51_count
' Check if data point is in Radius 8.5 group
ElseIf Worksheets("digester_output_part_2").Cells(i, 6).Value = 8.5 Then
    Radi_8_5_count = Radi_8_5_count + 1 ' add 1 to Radius 8.5 group's count
    ' calculate Radius 8.5 group's average
    Radi_8_5_ave = (Radi_8_5_ave * (Radi_8_5_count - 1) + _
        Worksheets("digester_output_part_2").Cells(i, 18).Value) / Radi_8_5_count
' Check if data point is in Radius 7.26 group
ElseIf Worksheets("digester_output_part_2").Cells(i, 6).Value = 7.26 Then
    Radi_7_26_count = Radi_7_26_count + 1 ' add 1 to Radius 7.26 group's count
    ' calculate Radius 7.26 group's average
    Radi_7_26_ave = (Radi_7_26_ave * (Radi_7_26_count - 1) + _
        Worksheets("digester_output_part_2").Cells(i, 18).Value) / Radi_7_26_count
' Check if data point is in Radius 5.13 group
```

```
    ElseIf Worksheets("digester_output_part_2").Cells(i, 6).Value = 5.13 Then
        Radi_5_13_count = Radi_5_13_count + 1 ' add 1 to Radius 5.13 group's count
        ' calculate Radius 5.13 group's average
        Radi_5_13_ave = (Radi_5_13_ave * (Radi_5_13_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / Radi_5_13_count
    ' Check if data point is in Radius 4.19 group
    ElseIf Worksheets("digester_output_part_2").Cells(i, 6).Value = 4.19 Then
        Radi_4_19_count = Radi_4_19_count + 1 ' add 1 to Radius 4.19 group's count
        ' calculate Radius 4.19 group's average
        Radi_4_19_ave = (Radi_4_19_ave * (Radi_4_19_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / Radi_4_19_count
    ' Data point must be in Radius 2.96 group
    Else
        Radi_2_96_count = Radi_2_96_count + 1 ' add 1 to Radius 2.96 group's count
        ' calculate Radius 2.96 group's average
        Radi_2_96_ave = (Radi_2_96_ave * (Radi_2_96_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / Radi_2_96_count
    End If
Next

' ***************************ThickW, Column 7***************************************
' Variables to keep track of average heat requirement
Dim ThickW_H_ave, ThickW_M_ave, ThickW_L_ave As Double
ThickW_H_ave = 0
ThickW_M_ave = 0
ThickW_L_ave = 0

' Variables to count # of data points in high, medium (or reference), and low groups
```

```
Dim ThickW_H_count, ThickW_M_count, ThickW_L_count As Long
ThickW_H_count = 0
ThickW_M_count = 0
ThickW_L_count = 0

' Cycle through each row of data starting from row 3
For i = 2 To 60000
    ' Check if data point is in high group
    If Worksheets("digester_output_part_2").Cells(i, 7).Value = 0.4 Then
        ThickW_H_count = ThickW_H_count + 1 ' add 1 to high group's count
        ' calculate high group's average
        ThickW_H_ave = (ThickW_H_ave * (ThickW_H_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickW_H_count
    ' Check if data point is in medium group
    ElseIf Worksheets("digester_output_part_2").Cells(i, 7).Value = 0.3 Then
        ThickW_M_count = ThickW_M_count + 1 ' add 1 to medium group's count
        ' calculate medium group's average
        ThickW_M_ave = (ThickW_M_ave * (ThickW_M_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickW_M_count
    ' Data point must be in low group
    Else
        ThickW_L_count = ThickW_L_count + 1 ' add 1 to low group's count
        ' calculate low group's average
        ThickW_L_ave = (ThickW_L_ave * (ThickW_L_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickW_L_count
    End If
Next
```

```
' ***************************ThickF, Column 8**************************************

' Variables to keep track of average heat requirement

Dim ThickF_H_ave, ThickF_M_ave, ThickF_L_ave As Double

ThickF_H_ave = 0

ThickF_M_ave = 0

ThickF_L_ave = 0


' Variables to count # of data points in high, medium (or reference), and low groups

Dim ThickF_H_count, ThickF_M_count, ThickF_L_count As Long

ThickF_H_count = 0

ThickF_M_count = 0

ThickF_L_count = 0


' Cycle through each row of data starting from row 3

For i = 2 To 60000

  ' Check if data point is in high group

  If Worksheets("digester_output_part_2").Cells(i, 8).Value = 0.4 Then

    ThickF_H_count = ThickF_H_count + 1 ' add 1 to high group's count

    ' calculate high group's average

    ThickF_H_ave = (ThickF_H_ave * (ThickF_H_count - 1) + _

      Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickF_H_count

  ' Check if data point is in medium group

  ElseIf Worksheets("digester_output_part_2").Cells(i, 8).Value = 0.3 Then

    ThickF_M_count = ThickF_M_count + 1 ' add 1 to medium group's count

    ' calculate medium group's average

    ThickF_M_ave = (ThickF_M_ave * (ThickF_M_count - 1) + _

      Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickF_M_count

  ' Data point must be in low group
```

```
    Else
      ThickF_L_count = ThickF_L_count + 1 ' add 1 to low group's count
      ' calculate low group's average
      ThickF_L_ave = (ThickF_L_ave * (ThickF_L_count - 1) + _
        Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickF_L_count
    End If
  Next

  ' ***************************ThickWin, Column
9**************************************
  ' Variables to keep track of average heat requirement
  Dim ThickWin_H_ave, ThickWin_M_ave, ThickWin_L_ave As Double
  ThickWin_H_ave = 0
  ThickWin_M_ave = 0
  ThickWin_L_ave = 0

  ' Variables to count # of data points in high, medium (or reference), and low groups
  Dim ThickWin_H_count, ThickWin_M_count, ThickWin_L_count As Long
  ThickWin_H_count = 0
  ThickWin_M_count = 0
  ThickWin_L_count = 0

  ' Cycle through each row of data starting from row 3
  For i = 2 To 60000
    ' Check if data point is in high group
    If Worksheets("digester_output_part_2").Cells(i, 9).Value = 0.07 Then
      ThickWin_H_count = ThickWin_H_count + 1 ' add 1 to high group's count
      ' calculate high group's average
```

```
        ThickWin_H_ave = (ThickWin_H_ave * (ThickWin_H_count - 1) + _
          Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickWin_H_count
      ' Check if data point is in medium group
      ElseIf Worksheets("digester_output_part_2").Cells(i, 9).Value = 0.05 Then
        ThickWin_M_count = ThickWin_M_count + 1 ' add 1 to medium group's count
        ' calculate medium group's average
        ThickWin_M_ave = (ThickWin_M_ave * (ThickWin_M_count - 1) + _
          Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickWin_M_count
      ' Data point must be in low group
      Else
        ThickWin_L_count = ThickWin_L_count + 1 ' add 1 to low group's count
        ' calculate low group's average
        ThickWin_L_ave = (ThickWin_L_ave * (ThickWin_L_count - 1) + _
          Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickWin_L_count
      End If
    Next

    ' ***************************ThickFin, Column
10**************************************
    ' Variables to keep track of average heat requirement
    Dim ThickFin_H_ave, ThickFin_M_ave, ThickFin_L_ave As Double
    ThickFin_H_ave = 0
    ThickFin_M_ave = 0
    ThickFin_L_ave = 0

    ' Variables to count # of data points in high, medium (or reference), and low groups
    Dim ThickFin_H_count, ThickFin_M_count, ThickFin_L_count As Long
    ThickFin_H_count = 0
```

```
ThickFin_M_count = 0

ThickFin_L_count = 0


' Cycle through each row of data starting from row 3

For i = 2 To 60000

   ' Check if data point is in high group

   If Worksheets("digester_output_part_2").Cells(i, 10).Value = 0.07 Then

      ThickFin_H_count = ThickFin_H_count + 1 ' add 1 to high group's count

      ' calculate high group's average

      ThickFin_H_ave = (ThickFin_H_ave * (ThickFin_H_count - 1) + _

         Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickFin_H_count

   ' Check if data point is in medium group

   ElseIf Worksheets("digester_output_part_2").Cells(i, 10).Value = 0.05 Then

      ThickFin_M_count = ThickFin_M_count + 1 ' add 1 to medium group's count

      ' calculate medium group's average

      ThickFin_M_ave = (ThickFin_M_ave * (ThickFin_M_count - 1) + _

         Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickFin_M_count

   ' Data point must be in low group

   Else

      ThickFin_L_count = ThickFin_L_count + 1 ' add 1 to low group's count

      ' calculate low group's average

      ThickFin_L_ave = (ThickFin_L_ave * (ThickFin_L_count - 1) + _

         Worksheets("digester_output_part_2").Cells(i, 18).Value) / ThickFin_L_count

   End If

Next


' ***************************DkWall, Column 11**************************************

' Variables to keep track of average heat requirement
```

```
Dim DkWall_H_ave, DkWall_M_ave, DkWall_L_ave As Double
DkWall_H_ave = 0
DkWall_M_ave = 0
DkWall_L_ave = 0

' Variables to count # of data points in high, medium (or reference), and low groups
Dim DkWall_H_count, DkWall_M_count, DkWall_L_count As Long
DkWall_H_count = 0
DkWall_M_count = 0
DkWall_L_count = 0

' Cycle through each row of data starting from row 3
For i = 2 To 60000
  ' Check if data point is in high group
  If Worksheets("digester_output_part_2").Cells(i, 11).Value = 2.5 Then
    DkWall_H_count = DkWall_H_count + 1 ' add 1 to high group's count
    ' calculate high group's average
    DkWall_H_ave = (DkWall_H_ave * (DkWall_H_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkWall_H_count
  ' Check if data point is in medium group
  ElseIf Worksheets("digester_output_part_2").Cells(i, 11).Value = 1.5 Then
    DkWall_M_count = DkWall_M_count + 1 ' add 1 to medium group's count
    ' calculate medium group's average
    DkWall_M_ave = (DkWall_M_ave * (DkWall_M_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkWall_M_count
  ' Data point must be in low group
  Else
    DkWall_L_count = DkWall_L_count + 1 ' add 1 to low group's count
```

```
        ' calculate low group's average
        DkWall_L_ave = (DkWall_L_ave * (DkWall_L_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkWall_L_count
    End If
Next

' ***************************DkF, Column 12**************************************
' Variables to keep track of average heat requirement
Dim DkF_H_ave, DkF_M_ave, DkF_L_ave As Double
DkF_H_ave = 0
DkF_M_ave = 0
DkF_L_ave = 0

' Variables to count # of data points in high, medium (or reference), and low groups
Dim DkF_H_count, DkF_M_count, DkF_L_count As Long
DkF_H_count = 0
DkF_M_count = 0
DkF_L_count = 0

' Cycle through each row of data starting from row 3
For i = 2 To 60000
    ' Check if data point is in high group
    If Worksheets("digester_output_part_2").Cells(i, 12).Value = 2.5 Then
        DkF_H_count = DkF_H_count + 1 ' add 1 to high group's count
        ' calculate high group's average
        DkF_H_ave = (DkF_H_ave * (DkF_H_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkF_H_count
    ' Check if data point is in medium group
```

```
  ElseIf Worksheets("digester_output_part_2").Cells(i, 12).Value = 1.5 Then
    DkF_M_count = DkF_M_count + 1 ' add 1 to medium group's count
    ' calculate medium group's average
    DkF_M_ave = (DkF_M_ave * (DkF_M_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkF_M_count
  ' Data point must be in low group
  Else
    DkF_L_count = DkF_L_count + 1 ' add 1 to low group's count
    ' calculate low group's average
    DkF_L_ave = (DkF_L_ave * (DkF_L_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkF_L_count
  End If
Next

' ***************************DkIns, Column 13*************************************
' Variables to keep track of average heat requirement
Dim DkIns_H_ave, DkIns_M_ave, DkIns_L_ave As Double
DkIns_H_ave = 0
DkIns_M_ave = 0
DkIns_L_ave = 0

' Variables to count # of data points in high, medium (or reference), and low groups
Dim DkIns_H_count, DkIns_M_count, DkIns_L_count As Long
DkIns_H_count = 0
DkIns_M_count = 0
DkIns_L_count = 0

' Cycle through each row of data starting from row 3
```

```
For i = 2 To 60000
  ' Check if data point is in high group
  If Worksheets("digester_output_part_2").Cells(i, 13).Value = 0.25 Then
    DkIns_H_count = DkIns_H_count + 1 ' add 1 to high group's count
    ' calculate high group's average
    DkIns_H_ave = (DkIns_H_ave * (DkIns_H_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkIns_H_count
  ' Check if data point is in medium group
  ElseIf Worksheets("digester_output_part_2").Cells(i, 13).Value = 0.15 Then
    DkIns_M_count = DkIns_M_count + 1 ' add 1 to medium group's count
    ' calculate medium group's average
    DkIns_M_ave = (DkIns_M_ave * (DkIns_M_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkIns_M_count
  ' Data point must be in low group
  Else
    DkIns_L_count = DkIns_L_count + 1 ' add 1 to low group's count
    ' calculate low group's average
    DkIns_L_ave = (DkIns_L_ave * (DkIns_L_count - 1) + _
      Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkIns_L_count
  End If
Next

' ****************************DensSoil, Column
14***************************************
' Variables to keep track of average heat requirement
Dim DensSoil_H_ave, DensSoil_M_ave, DensSoil_L_ave As Double
DensSoil_H_ave = 0
DensSoil_M_ave = 0
```

```
DensSoil_L_ave = 0

' Variables to count # of data points in high, medium (or reference), and low groups
Dim DensSoil_H_count, DensSoil_M_count, DensSoil_L_count As Long
DensSoil_H_count = 0
DensSoil_M_count = 0
DensSoil_L_count = 0

' Cycle through each row of data starting from row 3
For i = 2 To 60000
    ' Check if data point is in high group
    If Worksheets("digester_output_part_2").Cells(i, 14).Value = 1600 Then
        DensSoil_H_count = DensSoil_H_count + 1 ' add 1 to high group's count
        ' calculate high group's average
        DensSoil_H_ave = (DensSoil_H_ave * (DensSoil_H_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / DensSoil_H_count
    ' Check if data point is in medium group
    ElseIf Worksheets("digester_output_part_2").Cells(i, 14).Value = 1450 Then
        DensSoil_M_count = DensSoil_M_count + 1 ' add 1 to medium group's count
        ' calculate medium group's average
        DensSoil_M_ave = (DensSoil_M_ave * (DensSoil_M_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / DensSoil_M_count
    ' Data point must be in low group
    Else
        DensSoil_L_count = DensSoil_L_count + 1 ' add 1 to low group's count
        ' calculate low group's average
        DensSoil_L_ave = (DensSoil_L_ave * (DensSoil_L_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / DensSoil_L_count
```

```
    End If
Next

' ***************************CpSoil, Column 15**************************************
' Variables to keep track of average heat requirement
Dim CpSoil_H_ave, CpSoil_M_ave, CpSoil_L_ave As Double
CpSoil_H_ave = 0
CpSoil_M_ave = 0
CpSoil_L_ave = 0

' Variables to count # of data points in high, medium (or reference), and low groups
Dim CpSoil_H_count, CpSoil_M_count, CpSoil_L_count As Long
CpSoil_H_count = 0
CpSoil_M_count = 0
CpSoil_L_count = 0

' Cycle through each row of data starting from row 3
For i = 2 To 60000
    ' Check if data point is in high group
    If Worksheets("digester_output_part_2").Cells(i, 15).Value = 1.92 Then
        CpSoil_H_count = CpSoil_H_count + 1 ' add 1 to high group's count
        ' calculate high group's average
        CpSoil_H_ave = (CpSoil_H_ave * (CpSoil_H_count - 1) + _
            Worksheets("digester_output_part_2").Cells(i, 18).Value) / CpSoil_H_count
    ' Check if data point is in medium group
    ElseIf Worksheets("digester_output_part_2").Cells(i, 15).Value = 0.835 Then
        CpSoil_M_count = CpSoil_M_count + 1 ' add 1 to medium group's count
        ' calculate medium group's average
```

```
      CpSoil_M_ave = (CpSoil_M_ave * (CpSoil_M_count - 1) + _
        Worksheets("digester_output_part_2").Cells(i, 18).Value) / CpSoil_M_count
    ' Data point must be in low group
    Else
      CpSoil_L_count = CpSoil_L_count + 1 ' add 1 to low group's count
      ' calculate low group's average
      CpSoil_L_ave = (CpSoil_L_ave * (CpSoil_L_count - 1) + _
        Worksheets("digester_output_part_2").Cells(i, 18).Value) / CpSoil_L_count
    End If
Next

' ***************************DkSoil, Column 16**************************************
' Variables to keep track of average heat requirement
Dim DkSoil_H_ave, DkSoil_M_ave, DkSoil_L_ave As Double
DkSoil_H_ave = 0
DkSoil_M_ave = 0
DkSoil_L_ave = 0

' Variables to count # of data points in high, medium (or reference), and low groups
Dim DkSoil_H_count, DkSoil_M_count, DkSoil_L_count As Long
DkSoil_H_count = 0
DkSoil_M_count = 0
DkSoil_L_count = 0

' Cycle through each row of data starting from row 3
For i = 2 To 60000
    ' Check if data point is in high group
    If Worksheets("digester_output_part_2").Cells(i, 16).Value = 1.94 Then
```

```
            DkSoil_H_count = DkSoil_H_count + 1 ' add 1 to high group's count
            ' calculate high group's average
            DkSoil_H_ave = (DkSoil_H_ave * (DkSoil_H_count - 1) + _
                Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkSoil_H_count
        ' Check if data point is in medium group
        ElseIf Worksheets("digester_output_part_2").Cells(i, 16).Value = 1 Then
            DkSoil_M_count = DkSoil_M_count + 1 ' add 1 to medium group's count
            ' calculate medium group's average
            DkSoil_M_ave = (DkSoil_M_ave * (DkSoil_M_count - 1) + _
                Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkSoil_M_count
        ' Data point must be in low group
        Else
            DkSoil_L_count = DkSoil_L_count + 1 ' add 1 to low group's count
            ' calculate low group's average
            DkSoil_L_ave = (DkSoil_L_ave * (DkSoil_L_count - 1) + _
                Worksheets("digester_output_part_2").Cells(i, 18).Value) / DkSoil_L_count
        End If
    Next

' ********************************************************************************************
' ********************************************************************************************
' *************************Output to WorkSheet: Results**********************************
' ********************************************************************************************
' ********************************************************************************************

    ' Add new worksheet named Results
    Sheets.Add(After:=Sheets(Sheets.Count)).Name = "Results"
```

```
' **********************Headings**************************
Range("B1").Select
ActiveCell.FormulaR1C1 = "Group"
Range("C1").Select
ActiveCell.FormulaR1C1 = "Value"
Range("D1").Select
ActiveCell.FormulaR1C1 = "# Observations"
Range("E1").Select
ActiveCell.FormulaR1C1 = "Avg. Heat Req."

' *************************T_m6***************************
' Write name of variable
Range("A2").Select
ActiveCell.FormulaR1C1 = "T_m6"

' Fill High group's values
Range("B2").Select
ActiveCell.FormulaR1C1 = "High"
Range("C2").Select
ActiveCell.FormulaR1C1 = "86"
Range("D2").Select
ActiveCell.FormulaR1C1 = Temp_H_count
Range("E2").Select
ActiveCell.FormulaR1C1 = Temp_H_ave

' Fill Medium (or reference) group's values
Range("B3").Select
ActiveCell.FormulaR1C1 = "Reference"
```

```
Range("C3").Select
ActiveCell.FormulaR1C1 = "66.2"
Range("D3").Select
ActiveCell.FormulaR1C1 = Temp_M_count
Range("E3").Select
ActiveCell.FormulaR1C1 = Temp_M_ave

' Fill Low group's values
Range("B4").Select
ActiveCell.FormulaR1C1 = "Low"
Range("C4").Select
ActiveCell.FormulaR1C1 = "41"
Range("D4").Select
ActiveCell.FormulaR1C1 = Temp_L_count
Range("E4").Select
ActiveCell.FormulaR1C1 = Temp_L_ave

' **************************HRT****************************
' Write name of variable
Range("A6").Select
ActiveCell.FormulaR1C1 = "HRT"

' Fill High group's values
Range("B6").Select
ActiveCell.FormulaR1C1 = "High"
Range("C6").Select
ActiveCell.FormulaR1C1 = "40"
Range("D6").Select
```

```
ActiveCell.FormulaR1C1 = HRT_H_count
Range("E6").Select
ActiveCell.FormulaR1C1 = HRT_H_ave

' Fill Medium (or reference) group's values
Range("B7").Select
ActiveCell.FormulaR1C1 = "Reference"
Range("C7").Select
ActiveCell.FormulaR1C1 = "22"
Range("D7").Select
ActiveCell.FormulaR1C1 = HRT_M_count
Range("E7").Select
ActiveCell.FormulaR1C1 = HRT_M_ave

' Fill Low group's values
Range("B8").Select
ActiveCell.FormulaR1C1 = "Low"
Range("C8").Select
ActiveCell.FormulaR1C1 = "8"
Range("D8").Select
ActiveCell.FormulaR1C1 = HRT_L_count
Range("E8").Select
ActiveCell.FormulaR1C1 = HRT_L_ave

' *************************Flow_m***************************
' Write name of variable
Range("A10").Select
ActiveCell.FormulaR1C1 = "Flow_m"
```

```
' Fill High group's values
Range("B10").Select
ActiveCell.FormulaR1C1 = "High"
Range("C10").Select
ActiveCell.FormulaR1C1 = "120"
Range("D10").Select
ActiveCell.FormulaR1C1 = FlowM_H_count
Range("E10").Select
ActiveCell.FormulaR1C1 = FlowM_H_ave

' Fill Medium (or reference) group's values
Range("B11").Select
ActiveCell.FormulaR1C1 = "Reference"
Range("C11").Select
ActiveCell.FormulaR1C1 = "60"
Range("D11").Select
ActiveCell.FormulaR1C1 = FlowM_M_count
Range("E11").Select
ActiveCell.FormulaR1C1 = FlowM_M_ave

' Fill Low group's values
Range("B12").Select
ActiveCell.FormulaR1C1 = "Low"
Range("C12").Select
ActiveCell.FormulaR1C1 = "40"
Range("D12").Select
ActiveCell.FormulaR1C1 = FlowM_L_count
```

```
Range("E12").Select
ActiveCell.FormulaR1C1 = FlowM_L_ave

' **********************Radi AND Rect***************************
' Fill for Radi
' Write name of variable
Range("A14").Select
ActiveCell.FormulaR1C1 = "Radius 16.23"
Range("A15").Select
ActiveCell.FormulaR1C1 = "Radius 11.48"
Range("A16").Select
ActiveCell.FormulaR1C1 = "Radius 2.96"
Range("A18").Select
ActiveCell.FormulaR1C1 = "Radius 12"
Range("A19").Select
ActiveCell.FormulaR1C1 = "Radius 8.5"
Range("A20").Select
ActiveCell.FormulaR1C1 = "Radius 8.51"
Range("A22").Select
ActiveCell.FormulaR1C1 = "Radius 7.26"
Range("A23").Select
ActiveCell.FormulaR1C1 = "Radius 5.13"
Range("A24").Select
ActiveCell.FormulaR1C1 = "Radius 4.19"

' Fill in Count
Range("B14").Select
ActiveCell.FormulaR1C1 = Radi_16_23_count
```

```
Range("B15").Select
ActiveCell.FormulaR1C1 = Radi_11_48_count
Range("B16").Select
ActiveCell.FormulaR1C1 = Radi_2_96_count
Range("B18").Select
ActiveCell.FormulaR1C1 = Radi_12_count
Range("B19").Select
ActiveCell.FormulaR1C1 = Radi_8_5_count
Range("B20").Select
ActiveCell.FormulaR1C1 = Radi_8_51_count
Range("B22").Select
ActiveCell.FormulaR1C1 = Radi_7_26_count
Range("B23").Select
ActiveCell.FormulaR1C1 = Radi_5_13_count
Range("B24").Select
ActiveCell.FormulaR1C1 = Radi_4_19_count

' Fill in Heat Requirement Average
Range("C14").Select
ActiveCell.FormulaR1C1 = Radi_16_23_ave
Range("C15").Select
ActiveCell.FormulaR1C1 = Radi_11_48_ave
Range("C16").Select
ActiveCell.FormulaR1C1 = Radi_2_96_ave
Range("C18").Select
ActiveCell.FormulaR1C1 = Radi_12_ave
Range("C19").Select
ActiveCell.FormulaR1C1 = Radi_8_5_ave
```

```
    Range("C20").Select
    ActiveCell.FormulaR1C1 = Radi_8_51_ave
    Range("C22").Select
    ActiveCell.FormulaR1C1 = Radi_7_26_ave
    Range("C23").Select
    ActiveCell.FormulaR1C1 = Radi_5_13_ave
    Range("C24").Select
    ActiveCell.FormulaR1C1 = Radi_4_19_ave

' *****Fill for Rect*****
    ' Write name of variable
    Range("E14").Select
    ActiveCell.FormulaR1C1 = "Rect 16.23"
    Range("E15").Select
    ActiveCell.FormulaR1C1 = "Rect 11.48"
    Range("E16").Select
    ActiveCell.FormulaR1C1 = "Rect 2.96"
    Range("E18").Select
    ActiveCell.FormulaR1C1 = "Rect 12"
    Range("E19").Select
    ActiveCell.FormulaR1C1 = "Rect 8.5"
    Range("E20").Select
    ActiveCell.FormulaR1C1 = "Rect 8.51"
    Range("E22").Select
    ActiveCell.FormulaR1C1 = "Rect 7.26"
    Range("E23").Select
    ActiveCell.FormulaR1C1 = "Rect 5.13"
    Range("E24").Select
```

```
ActiveCell.FormulaR1C1 = "Rect 4.19"

' Fill in Count
Range("F14").Select
ActiveCell.FormulaR1C1 = Rect_16_23_count
Range("F15").Select
ActiveCell.FormulaR1C1 = Rect_11_48_count
Range("F16").Select
ActiveCell.FormulaR1C1 = Rect_2_96_count
Range("F18").Select
ActiveCell.FormulaR1C1 = Rect_12_count
Range("F19").Select
ActiveCell.FormulaR1C1 = Rect_8_5_count
Range("F20").Select
ActiveCell.FormulaR1C1 = Rect_8_51_count
Range("F22").Select
ActiveCell.FormulaR1C1 = Rect_7_26_count
Range("F23").Select
ActiveCell.FormulaR1C1 = Rect_5_13_count
Range("F24").Select
ActiveCell.FormulaR1C1 = Rect_4_19_count

' Fill in Heat Requirement Average
Range("G14").Select
ActiveCell.FormulaR1C1 = Rect_16_23_ave
Range("G15").Select
ActiveCell.FormulaR1C1 = Rect_11_48_ave
Range("G16").Select
```

```
ActiveCell.FormulaR1C1 = Rect_2_96_ave
Range("G18").Select
ActiveCell.FormulaR1C1 = Rect_12_ave
Range("G19").Select
ActiveCell.FormulaR1C1 = Rect_8_5_ave
Range("G20").Select
ActiveCell.FormulaR1C1 = Rect_8_51_ave
Range("G22").Select
ActiveCell.FormulaR1C1 = Rect_7_26_ave
Range("G23").Select
ActiveCell.FormulaR1C1 = Rect_5_13_ave
Range("G24").Select
ActiveCell.FormulaR1C1 = Rect_4_19_ave

' *************************Thick_w***************************
' Write name of variable
Range("A26").Select
ActiveCell.FormulaR1C1 = "ThickW"

' Fill High group's values
Range("B26").Select
ActiveCell.FormulaR1C1 = "High"
Range("C26").Select
ActiveCell.FormulaR1C1 = ".4"
Range("D26").Select
ActiveCell.FormulaR1C1 = ThickW_H_count
Range("E26").Select
ActiveCell.FormulaR1C1 = ThickW_H_ave
```

```
' Fill Medium (or reference) group's values
Range("B27").Select
ActiveCell.FormulaR1C1 = "Reference"
Range("C27").Select
ActiveCell.FormulaR1C1 = ".3"
Range("D27").Select
ActiveCell.FormulaR1C1 = ThickW_M_count
Range("E27").Select
ActiveCell.FormulaR1C1 = ThickW_M_ave

' Fill Low group's values
Range("B28").Select
ActiveCell.FormulaR1C1 = "Low"
Range("C28").Select
ActiveCell.FormulaR1C1 = ".2"
Range("D28").Select
ActiveCell.FormulaR1C1 = ThickW_L_count
Range("E28").Select
ActiveCell.FormulaR1C1 = ThickW_L_ave

' *************************Thick_f***************************
' Write name of variable
Range("A30").Select
ActiveCell.FormulaR1C1 = "Thick_f"

' Fill High group's values
Range("B30").Select
```

```
ActiveCell.FormulaR1C1 = "High"
Range("C30").Select
ActiveCell.FormulaR1C1 = ".4"
Range("D30").Select
ActiveCell.FormulaR1C1 = ThickF_H_count
Range("E30").Select
ActiveCell.FormulaR1C1 = ThickF_H_ave

' Fill Medium (or reference) group's values
Range("B31").Select
ActiveCell.FormulaR1C1 = "Reference"
Range("C31").Select
ActiveCell.FormulaR1C1 = ".3"
Range("D31").Select
ActiveCell.FormulaR1C1 = ThickF_M_count
Range("E31").Select
ActiveCell.FormulaR1C1 = ThickF_M_ave

' Fill Low group's values
Range("B32").Select
ActiveCell.FormulaR1C1 = "Low"
Range("C32").Select
ActiveCell.FormulaR1C1 = ".2"
Range("D32").Select
ActiveCell.FormulaR1C1 = ThickF_L_count
Range("E32").Select
ActiveCell.FormulaR1C1 = ThickF_L_ave
```

```
' *************************ThickWin***************************

' Write name of variable

Range("A34").Select

ActiveCell.FormulaR1C1 = "Thick_win"


' Fill High group's values

Range("B34").Select

ActiveCell.FormulaR1C1 = "High"

Range("C34").Select

ActiveCell.FormulaR1C1 = "0.07"

Range("D34").Select

ActiveCell.FormulaR1C1 = ThickWin_H_count

Range("E34").Select

ActiveCell.FormulaR1C1 = ThickWin_H_ave


' Fill Medium (or reference) group's values

Range("B35").Select

ActiveCell.FormulaR1C1 = "Reference"

Range("C35").Select

ActiveCell.FormulaR1C1 = ".05"

Range("D35").Select

ActiveCell.FormulaR1C1 = ThickWin_M_count

Range("E35").Select

ActiveCell.FormulaR1C1 = ThickWin_M_ave


' Fill Low group's values

Range("B36").Select

ActiveCell.FormulaR1C1 = "Low"
```

```
Range("C36").Select
ActiveCell.FormulaR1C1 = ".03"
Range("D36").Select
ActiveCell.FormulaR1C1 = ThickWin_L_count
Range("E36").Select
ActiveCell.FormulaR1C1 = ThickWin_L_ave

' *************************Thick_fin***************************
' Write name of variable
Range("A38").Select
ActiveCell.FormulaR1C1 = "Thick_fin"

' Fill High group's values
Range("B38").Select
ActiveCell.FormulaR1C1 = "High"
Range("C38").Select
ActiveCell.FormulaR1C1 = ".07"
Range("D38").Select
ActiveCell.FormulaR1C1 = ThickFin_H_count
Range("E38").Select
ActiveCell.FormulaR1C1 = ThickFin_H_ave

' Fill Medium (or reference) group's values
Range("B39").Select
ActiveCell.FormulaR1C1 = "Reference"
Range("C39").Select
ActiveCell.FormulaR1C1 = ".05"
Range("D39").Select
```

```
ActiveCell.FormulaR1C1 = ThickFin_M_count
Range("E39").Select
ActiveCell.FormulaR1C1 = ThickFin_M_ave

' Fill Low group's values
Range("B40").Select
ActiveCell.FormulaR1C1 = "Low"
Range("C40").Select
ActiveCell.FormulaR1C1 = ".03"
Range("D40").Select
ActiveCell.FormulaR1C1 = ThickFin_L_count
Range("E40").Select
ActiveCell.FormulaR1C1 = ThickFin_L_ave

' *************************DK_wall***************************
' Write name of variable
Range("A42").Select
ActiveCell.FormulaR1C1 = "DK_wall"

' Fill High group's values
Range("B42").Select
ActiveCell.FormulaR1C1 = "High"
Range("C42").Select
ActiveCell.FormulaR1C1 = "2.5"
Range("D42").Select
ActiveCell.FormulaR1C1 = DkWall_H_count
Range("E42").Select
ActiveCell.FormulaR1C1 = DkWall_H_ave
```

```
' Fill Medium (or reference) group's values

Range("B43").Select

ActiveCell.FormulaR1C1 = "Reference"

Range("C43").Select

ActiveCell.FormulaR1C1 = "1.5"

Range("D43").Select

ActiveCell.FormulaR1C1 = DkWall_M_count

Range("E43").Select

ActiveCell.FormulaR1C1 = DkWall_M_ave


' Fill Low group's values

Range("B44").Select

ActiveCell.FormulaR1C1 = "Low"

Range("C44").Select

ActiveCell.FormulaR1C1 = "0.5"

Range("D44").Select

ActiveCell.FormulaR1C1 = DkWall_L_count

Range("E44").Select

ActiveCell.FormulaR1C1 = DkWall_L_ave


' **************************DK_f****************************

' Write name of variable

Range("A46").Select

ActiveCell.FormulaR1C1 = "DK_f"


' Fill High group's values

Range("B46").Select
```

```
ActiveCell.FormulaR1C1 = "High"
Range("C46").Select
ActiveCell.FormulaR1C1 = "2.5"
Range("D46").Select
ActiveCell.FormulaR1C1 = DkF_H_count
Range("E46").Select
ActiveCell.FormulaR1C1 = DkF_H_ave

' Fill Medium (or reference) group's values
Range("B47").Select
ActiveCell.FormulaR1C1 = "Reference"
Range("C47").Select
ActiveCell.FormulaR1C1 = "1.5"
Range("D47").Select
ActiveCell.FormulaR1C1 = DkF_M_count
Range("E47").Select
ActiveCell.FormulaR1C1 = DkF_M_ave

' Fill Low group's values
Range("B48").Select
ActiveCell.FormulaR1C1 = "Low"
Range("C48").Select
ActiveCell.FormulaR1C1 = "0.5"
Range("D48").Select
ActiveCell.FormulaR1C1 = DkF_L_count
Range("E48").Select
ActiveCell.FormulaR1C1 = DkF_L_ave
```

```
' *************************DK_ins***************************
' Write name of variable
Range("A50").Select
ActiveCell.FormulaR1C1 = "DK_ins"

' Fill High group's values
Range("B50").Select
ActiveCell.FormulaR1C1 = "High"
Range("C50").Select
ActiveCell.FormulaR1C1 = ".25"
Range("D50").Select
ActiveCell.FormulaR1C1 = DkIns_H_count
Range("E50").Select
ActiveCell.FormulaR1C1 = DkIns_H_ave

' Fill Medium (or reference) group's values
Range("B51").Select
ActiveCell.FormulaR1C1 = "Reference"
Range("C51").Select
ActiveCell.FormulaR1C1 = ".15"
Range("D51").Select
ActiveCell.FormulaR1C1 = DkIns_M_count
Range("E51").Select
ActiveCell.FormulaR1C1 = DkIns_M_ave

' Fill Low group's values
Range("B52").Select
ActiveCell.FormulaR1C1 = "Low"
```

```
Range("C52").Select
ActiveCell.FormulaR1C1 = ".05"
Range("D52").Select
ActiveCell.FormulaR1C1 = DkIns_L_count
Range("E52").Select
ActiveCell.FormulaR1C1 = DkIns_L_ave

' *************************DEN_soil***************************
' Write name of variable
Range("A54").Select
ActiveCell.FormulaR1C1 = "DEN_soil"

' Fill High group's values
Range("B54").Select
ActiveCell.FormulaR1C1 = "High"
Range("C54").Select
ActiveCell.FormulaR1C1 = "1600"
Range("D54").Select
ActiveCell.FormulaR1C1 = DensSoil_H_count
Range("E54").Select
ActiveCell.FormulaR1C1 = DensSoil_H_ave

' Fill Medium (or reference) group's values
Range("B55").Select
ActiveCell.FormulaR1C1 = "Reference"
Range("C55").Select
ActiveCell.FormulaR1C1 = "1450"
Range("D55").Select
```

```
ActiveCell.FormulaR1C1 = DensSoil_M_count
Range("E55").Select
ActiveCell.FormulaR1C1 = DensSoil_M_ave

' Fill Low group's values
Range("B56").Select
ActiveCell.FormulaR1C1 = "Low"
Range("C56").Select
ActiveCell.FormulaR1C1 = "1200"
Range("D56").Select
ActiveCell.FormulaR1C1 = DensSoil_L_count
Range("E56").Select
ActiveCell.FormulaR1C1 = DensSoil_L_ave

' *************************CP_soil***************************
' Write name of variable
Range("A58").Select
ActiveCell.FormulaR1C1 = "CP_soil"

' Fill High group's values
Range("B58").Select
ActiveCell.FormulaR1C1 = "High"
Range("C58").Select
ActiveCell.FormulaR1C1 = "1.92"
Range("D58").Select
ActiveCell.FormulaR1C1 = CpSoil_H_count
Range("E58").Select
ActiveCell.FormulaR1C1 = CpSoil_H_ave
```

```
' Fill Medium (or reference) group's values
Range("B59").Select
ActiveCell.FormulaR1C1 = "Reference"
Range("C59").Select
ActiveCell.FormulaR1C1 = ".835"
Range("D59").Select
ActiveCell.FormulaR1C1 = CpSoil_M_count
Range("E59").Select
ActiveCell.FormulaR1C1 = CpSoil_M_ave

' Fill Low group's values
Range("B60").Select
ActiveCell.FormulaR1C1 = "Low"
Range("C60").Select
ActiveCell.FormulaR1C1 = ".8"
Range("D60").Select
ActiveCell.FormulaR1C1 = CpSoil_L_count
Range("E60").Select
ActiveCell.FormulaR1C1 = CpSoil_L_ave

' *************************DK_Soil***************************
' Write name of variable
Range("A62").Select
ActiveCell.FormulaR1C1 = "DK_Soil"

' Fill High group's values
Range("B62").Select
```

```
ActiveCell.FormulaR1C1 = "High"
Range("C62").Select
ActiveCell.FormulaR1C1 = "1.94"
Range("D62").Select
ActiveCell.FormulaR1C1 = DkSoil_H_count
Range("E62").Select
ActiveCell.FormulaR1C1 = DkSoil_H_ave

' Fill Medium (or reference) group's values
Range("B63").Select
ActiveCell.FormulaR1C1 = "Reference"
Range("C63").Select
ActiveCell.FormulaR1C1 = "1"
Range("D63").Select
ActiveCell.FormulaR1C1 = DkSoil_M_count
Range("E63").Select
ActiveCell.FormulaR1C1 = DkSoil_M_ave

' Fill Low group's values
Range("B64").Select
ActiveCell.FormulaR1C1 = "Low"
Range("C64").Select
ActiveCell.FormulaR1C1 = ".19"
Range("D64").Select
ActiveCell.FormulaR1C1 = DkSoil_L_count
Range("E64").Select
ActiveCell.FormulaR1C1 = DkSoil_L_ave
```

```
'**************************Format Data**********************************
'*******Enter Headings********
Range("A1").Select
ActiveCell.FormulaR1C1 = "Variable"
Range("B1").Select
ActiveCell.FormulaR1C1 = "Group"
Range("C1").Select
ActiveCell.FormulaR1C1 = "Value"
Range("D1").Select
ActiveCell.FormulaR1C1 = "# Oservations"
Range("E1").Select
ActiveCell.FormulaR1C1 = "Avg. Heat Req."

'********Format Row 1*********
Rows("1:1").Select                      ' Select Row 1
Selection.Font.Bold = True              ' Make Bold
Selection.HorizontalAlignment = xlCenter   ' Center text
Selection.Font.Size = 12                ' Make text larger

' Create Bottom Border for Row 1
With Selection.Borders(xlEdgeBottom)
   .LineStyle = xlContinuous
   .ColorIndex = 0
   .TintAndShade = 0
   .Weight = xlThick
End With

'********Format Column A*********
```

```
Columns("A:A").Select                  ' Select Row
Selection.Font.Bold = True             ' Make Bold
Selection.HorizontalAlignment = xlCenter ' Center Text

'********Rectangular Headings********
Range("E14:E24").Select                ' Select Cells
Selection.Font.Bold = True             ' Make Bold
Selection.HorizontalAlignment = xlCenter    ' Center Text

'********Add Border to Radi and Rect Block******************
Range("A14:G24").Select

With Selection.Borders(xlEdgeLeft)
   .LineStyle = xlContinuous
   .ColorIndex = 0
   .TintAndShade = 0
   .Weight = xlMedium
End With
With Selection.Borders(xlEdgeTop)
   .LineStyle = xlContinuous
   .ColorIndex = 0
   .TintAndShade = 0
   .Weight = xlMedium
End With
With Selection.Borders(xlEdgeBottom)
   .LineStyle = xlContinuous
   .ColorIndex = 0
   .TintAndShade = 0
```

```
        .Weight = xlMedium
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlMedium
    End With

    '********Auto Fit Columns********
    Columns("A:G").EntireColumn.AutoFit
End Sub
```