Smart Pavements

A Major Qualifying Project
Submitted to the Faculty of
Worcester Polytechnic Institute
In Partial Fulfillment of the requirements for
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in Civil Engineering

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Abstract

As the need for alternative energy sources continues to grow, many have pointed towards renewable energy resources as a way to fix the global energy crisis. One possible way to better utilize the natural resources of the Earth would be to harvest the solar energy captured by asphalt pavements. This report explains the previous research that has been conducted in this field and then explains specific details of the design of an underground piping system, or a Smart Pavement, which would transfer the thermal energy of an asphalt pavement to a liquid. The liquid could later be used in the heating or water systems of nearby buildings and/or could be used to melt snow and ice in the winter months, thus reducing the use of conventional energy sources and the need for seasonal maintenance.

Acknowledgements

We would like to first thank Worcester Polytechnic Institute (WPI) and the Civil Engineering Department for giving us the opportunity to complete this project. We would like to especially thank our advisors, Professor Rajib Mallick, an associate professor of the Civil Engineering Department, and Professor Mingjiang Tao, and Assistant Professor of the Civil Engineering Department.

We would additionally like to thank two other members of the Worcester Polytechnic Institute Faculty who helped significantly with the completion of this Master Qualifying Project (MQP). First, Dean Daigneault, the Principal Lab Machinist in the Kaven Hall Shop, for allowing us to use the lab equipment necessary for the temperature testing conducted in the Kaven Hall parking lot. Dean also directed us to the correct resources when trying to find large databases of pipes to be used for our MQP.

Second, we would like to thank James Monaco, the Multimedia Production Specialist for the Academic Technology Center at WPI, who helped us produce a flash animation that summarized the ideas of our MQP into one simple and easy to understand animation. Without the help of James, we would never have been able to create such a professional looking animation.

Authorship Page

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Recommendations, Appendix A

Derek – II.2, II.4, III.3, III.4, V

Table of Contents

List of Figures

List of Tables

I   Introduction

Due to the looming consequences of global warming, the need for finding cleaner and more efficient forms of energy continues to grow. In order to find practical forms of alternative energies, many researchers are attempting to create ways of manipulating our current infrastructure to produce the energy that we need, such as putting solar panels on rooftops or placing wind turbines in windy areas. However, these alternative ways of producing energy are sometimes controversial because many residents believe that solar panels and wind turbines may look out of place or would cause a noise disturbance. The ideal way of producing energy would be to have it be renewable or environmentally friendly while at the same time being accepted for use in a residential or office setting.

One possibility for alternative energy production may be found in capturing the thermal energy which is entrapped in asphalt pavements, specifically parking lot pavements. Asphalt pavements can collect a large amount of thermal energy from the sun no matter what time of year. Asphalt also has a low thermal conductivity and high heat capacity and thus asphalt pavements behave as heat reservoirs. Field data has suggested that some asphalt pavements can reach maximum surface temperatures of over 150 degrees Fahrenheit[1]. A way to better utilize this phenomena would be to transfer the stored thermal energy in the pavement to a system which could use the thermal energy in a more beneficial way.

One theoretical design, known as a Smart Pavement and shown below in Figure 1, would use a solar heat pump to pump a liquid through a piping system placed just beneath the surface of the parking lot. This process would transfer the heat energy of the pavement into the liquid. After the liquid is heated, it would be stored in the insulated reservoir; the stored liquid could then be used in nearby buildings for heating and hot water systems, or it could be used to melt snow and ice that covers the surface of the parking lot in the winter. The process of removing thermal energy from the pavement can also reduce the temperature of the pavement, reducing a phenomenon known as the Urban Heat Island Effect in addition to extending the lifespan of

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[1] Chen, Bhowmick, and Mallick. (2008). Harvesting Energy from Asphalt Pavements and Reducing the Heat Island Effect

the pavement[2].

Hot Water Coming out of Pipe into an Insulated Reservoir in the Base or Subbase Area inside the Pavement

Temperature of Pavement Drops and Radiated Heat is Reduced; Pavement Life is Extended, and Energy Comsumptions of Adjacent Buildings are Reduced and Air quality is Improved

Solar Pump Pumps Cold Water through Pipes in the Asphalt Pavement

Solar Heating Element inside Insulated Reservoir Increases Water Temperature as Required

Adequately Hot Water Comes Out for Use as Hot Water or for Heating Other Fluid in Turbine for Generating Electricity Using Systems such as Organic Rankine Cycle or Kalina Cycle

Figure 1: Conceptual Design of System[3]

Recent research conducted by Professor Rajib Mallick, an associate professor of the Civil Engineering Department at Worcester Polytechnic Institute (WPI) in Worcester, MA, has shown that this process is not only possible, but could be implemented with some minor adjustments to current pavement infrastructure[4]. However, further research is needed in determining the proper materials to be used for the heat exchanger (the pipes that would be laid underneath the pavement). A system must also be developed that can determine what length of a given pipe would be needed to heat the liquid in the system to a desired temperature. For instance, if water were to be used in the system, it could be heated up to 50°C and used in residential and commercial settings as domestic hot water. Hot enough liquids could also be used to run a

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[2] Ibid
[3] Chen, Bhowmick, and Mallick. (2008). Harvesting Energy from Asphalt Pavements and Reducing the Heat Island Effect
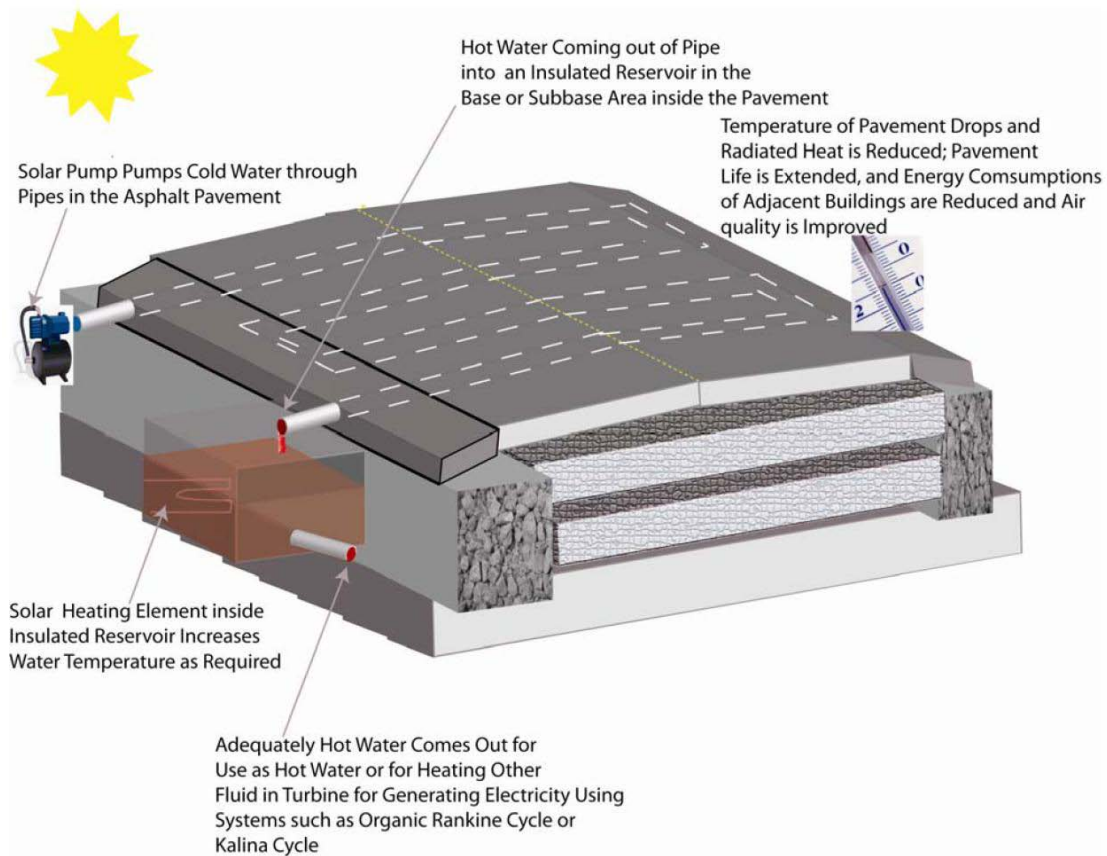[4] Ibid

turbine or other types of generators which could produce electricity for use in nearby buildings.

The following report will create a design for a Smart Pavement to be placed in a parking lot at the WPI campus. The parking lot is located between the school's library, Gordon Library, and the Civil Engineering building, Kaven Hall, and is shown below in Figure 2. The Smart Pavement that will be designed will use water as its liquid. The method which was developed for identifying the proper materials for the heat exchanger and the fluid to be used in the pipe will be explained. The report will also explore possible ideas for including an insulated reservoir, either underground or in the building, which would be used to store excess heated liquid. Lastly, recommendations for how to conduct further research regarding this project will be given.
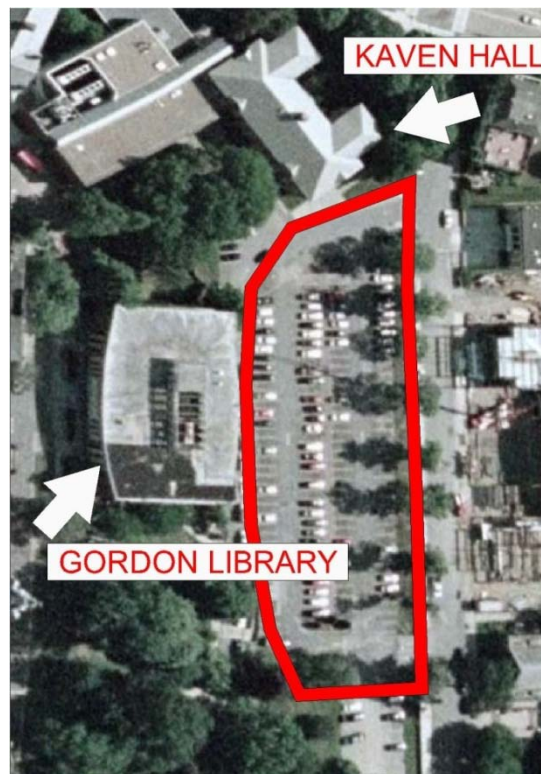

Figure 2: Kaven Hall Parking Lot[5]

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[5] Google Earth

II   Background Research

This chapter summarizes the background research conducted throughout the course of the project. The chapter first introduces the major problems and phenomena that occur in the world that have resulted in the need for creating a Smart Pavement. Phenomena explained are Global Warming and the Urban Island Heat Effect; special attention is paid to the idea that pavements are strong collectors of thermal energy and are thus adding to the effects of global warming. There is then a summary of field data collected by members of the Wisconsin Department of Transportation, and another set of data collected by WPI professors and students, which shows that pavements in the Worcester area, specifically the parking lot which is the focus of this study, become hot enough at certain times of the year to warrant the installation of a Smart Pavement.

II.1   *Global Warming*

Global warming is an average increase in the Earth's temperature and has been attributed to human activity; scientists believe that our use of fossil fuels, aerosols and other chemicals have resulted in a warming of the Earth's surface[6]. Scientists further believe that if global warming continues at its current level, it will result in massive climate change and would create abnormal and dangerous weather patterns across the world[7]. Because of the potentially catastrophic consequences that can result from global warming, there have been worldwide movements to attempt to go "green", become more sustainable and reduce the level of carbon emissions that humans produce. The reasons for global warming have been strongly attributed to the phenomena known as the Greenhouse Effect.

The Greenhouse Effect is "the warming effect felt on Earth's surface, produced by

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[6] IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[7] United States Environmental Protection Agency. (2006). Climate change: What it is... Retrieved 1/2, 2009, from http://epa.gov/climatechange/kids/gw.html

greenhouse gases. These gases allow incoming solar radiation to pass through the Earth's atmosphere, but trap heat by preventing some of the infrared radiation from the Earth's surface from escaping to outer space. This process occurs naturally and has kept the Earth's temperature about 60 degrees Fahrenheit warmer than it would otherwise be."[8] The Greenhouse Effect relates to global warming in that many scientists believe that human activity, particularly the use of aerosols and the burning of fossil fuels, has dramatically increased the level of greenhouse gases in the atmosphere, thus raising the temperature of the Earth.

Asphalt pavement surfaces further add to the problem of global warming. Asphalt is used primarily for many roads throughout the world. As a material, asphalt is very absorbent of thermal energy and thus asphalt pavements further raise the Earth's surface temperature through an effect known as the Urban Heat Island Effect.

II.2   *The Urban Heat Island Effect*

The Urban Heat Island Effect is a phenomenon where an urban area has a higher average surface temperature than its surrounding rural areas. This can be caused by the removal of vegetation and replacement of that vegetation by asphalt pavements. Asphalt pavements absorb the heat from the sun, rather than reflecting it.[9] And because urban areas have denser population levels and use more energy than surrounding rural areas, while also containing more dark surfaces which absorb heat from the sun, such as rooftops and pavements, urban areas have higher average surface temperatures due to the fact that a "heat island" forms over the urban area. The term "heat island" refers to the imaginary island of heat which forms over the roads of the urban area; this island can cause the surface temperature to be anywhere from 1 to 11 degrees (Celsius) warmer than surrounding rural areas[10]. In turn, this phenomenon creates a greater need for energy use in the form of air conditioning, which further adds to the issue of global warming because of the thermal energy expended by the air

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[8] United States Environmental Protection Agency. (2006). Climate change: What it is... Retrieved 1/2, 2009, from http://epa.gov/climatechange/kids/gw.html
[9] Oke, T. R. "Boundary layer climates." 2nd Ed., Routledge, London, 1987.
[10] United States Environmental Protection Agency. (2009). *Heat island effect.* Retrieved 12/10, 2008, from http://www.epa.gov/heatisland/index.htm

conditioners. This creates a never ending problem of having to use more energy to cool off an urban area, but at the same time creating more heat, thus in the end further extending the effects of global warming perpetually.

While energy use and population levels are significant factors in the urban heat island effect, pavements have also been identified as a major contributor to the urban heat island effect. Pavements collect high levels of radiation from the sun, and as a result emit heat energy into the air.[11] According to Cambridge Systematics, in areas such as the Houston metropolitan area, about 60 percent of their transportation land use is in parking lot facilities.[12] With such a large use of land within parking lot facilities, in urban areas this effect is more significant as busy areas see a higher temperature during the day due to the fact that there are more roads and even dark rooftops which collect the sun's heat. Two alternatives to helping solve this issue are to create pavements which reflect more sunlight and are thus cooler or create pavements with alternative cooling systems which transfer the heat energy to nearby buildings. This project deals with the latter.

II.3   *Pavement Temperatures*

The common assumption regarding the temperature of a pavement is that its surface temperature is the same as the surrounding air temperature.[13] However, asphalt pavements absorb a large amount of the solar radiation they are exposed to; this leads to many pavements actually having higher surface temperatures than the surrounding air. In a recent Wisconsin Department of Transportation (WisDOT) field study, researchers found that "the pavement temperatures at all depths generally are higher than the air temperatures for much of the day, particularly during the night"[14]. The study focused on the following four depths, 6.4mm,

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[11] United States Environmental Protection Agency. (2009). *Heat island effect.* Retrieved 12/10, 2008, from http://www.epa.gov/heatisland/index.htm

[12] Cambridge Systematics, Inc. "Cool Pavement Report: EPA Cool Pavements Study - Task 5", prepared for Heat Island Reduction Initiative, U.S. Environmental Protection Agency, 2005.

[13] Peter J. Bosscher, Hussain U. Bahia, Suwitho Thomas, and Jeffrey S. Russell. (1998). Relationship between pavement temperature and weather data. *Transportation Research Record, 1609*

[14] Ibid

38.1mm, 69.9mm and 101.6mm. These four depths were important to the relevance of a Smart Pavement because the target distance below the surface for the pipes to be buried was 1.5 inches, or 38.1mm.

The WisDOT study also found that the minimum and maximum daily temperatures of a pavement surface were always higher than the corresponding average daily air temperature[15]. WisDOT also found that the temperature profile for a pavement has very distinct properties; during the day, the top layer is the warmest while the bottom is the coolest. During the night the bottom is the warmest layer while the top is the coolest. This shows that while the air temperature plays a strong part in determining the temperature of a pavement at certain depths, it is not the only factor. The temperature of the pavement at a certain depth depended on additional factors, including the amount of solar radiation that the pavement was able to absorb.

With this information, the WisDOT study also goes on to provide equations on how to find the temperature of a pavement at certain layers beneath the surface as long as the radiation values for that day are known and a minimum, or maximum, air temperature is known. These equations are included below:

$$T_{PAV@6.4\,mm\,(MIN)} = 2.27 + 0.778\,T_{AIR(MIN)} \tag{1}$$

$$T_{PAV@6.4\,mm\,(MIN)} = 6.83 + 1.014\,T_{AIR(MIN)} \tag{2}$$

Where $T_{PAV@6.4\,mm\,(MIN)}$ is the minimum pavement temperature at 6.4 mm (0.25 inches) below the surface and $T_{AIR(MIN)}$ is the minimum air temperature. Equation 1 is for air temperatures below 0°C and Equation 2 is for air temperatures above 0°C.

$$T_{PAV@6.4\,mm\,(MAX)} = -0.519 + 0.820\,T_{AIR(MAX)} + 0.00335\,Solar\_0 \tag{3}$$

$$T_{PAV@6.4\,mm\,(MAX)} = 2.811 + 1.087\,T_{AIR(MAX)} + 0.00246\,Solar\_0 \tag{4}$$

Where $T_{PAV@6.4\,mm\,(MAX)}$ is the maximum pavement temperature at 6.4 mm, $T_{AIR(MAX)}$ is the maximum air temperature and $Solar\_0$ is the daily total solar radiation intensity in W *

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[15] Ibid

hr/m^2. Equation 3 is for air temperatures below 0°C and Equation 4 is for air temperatures above 0°C.

Using the above equations, one can determine within a relatively accurate range the temperature of a pavement 6.4 millimeters under the surface. WisDOT identifies the accuracy for the equations to be within five percent of the actual temperature[16]. While the Smart Pavement has pipes that will be buried 1.5" below the ground, or 38.1 mm, the WisDOT study mentions that the temperatures below the surface of the pavement are always higher than the average air temperature and that there is little difference between the temperatures at the depth of 6.4mm and 38.1 mm[17]. Equation 4 is the most useful for this project, as the only temperatures that are of relevance to the Smart Pavement are those above 0°C. Any temperatures below 0°C are not useful for the scope of a Smart Pavement because the liquid in the system would not be hot enough for practical use. The WisDOT study also mentions that while all four equations yield resulting pavement temperatures, only Equation 4 takes into account solar radiation, which was found to be very important in determining the actual temperature of the pavement.

II.4   Previous MQP Work

Bao-Liang Chen, Sankha Bhowmick and Rajib Mallick have been working to develop a system to utilize the thermal energy within pavement, which would both provide an alternative energy source, as well as reduce the urban heat island effect. Their conceptual design can be seen in Figure 1. They have found the temperatures at different depths below the pavement surface, and it was seen that the temperature was higher when closer to the surface.

They proposed the usage of a system of pipes to reduce the urban heat island effect. But the heat removed from the pavements can provide solar energy or just hot water use. In addition, they have worked on trying to raise the conductivity of the pavements by using

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[16] Peter J. Bosscher, Hussain U. Bahia, Suwitho Thomas, and Jeffrey S. Russell. (1998). Relationship between pavement temperature and weather data. *Transportation Research Record, 1609*

[17] Peter J. Bosscher, Hussain U. Bahia, Suwitho Thomas, and Jeffrey S. Russell. (1998). Relationship between pavement temperature and weather data. *Transportation Research Record, 1609*

different types of aggregate in the asphalt, such as comparing quartzite and metagranodiorite mixes. Using a higher conductivity with pavement, more of the sun's heat could be transferred into the system of pipes rather than being reflected off the surface and causing more heat.

However, a use of an efficient heat exchanger needs to be explored.

II.5   MEPDG Data

MEPDG, or Mechanistic-Empirical Pavement Design Guide, is a computer program that lets a user perform an analysis based on the location of a pavement structure. In order to further prove that pavement life is extended by reducing the temperature of the pavement, analyses were completed of four different cities in the United States to see how the change in maximum temperature affected the performance of a pavement. The four cities used were Houston, Texas; Chicago, Illinois; Raleigh, North Carolina; and Portland, Maine. The maximum temperature for each city was, respectively, 70°C, 64°C, 58°C, 52°C.

After running the four analyses, the rutting data was checked for each city. Values are presented for numerous parameters over a span of 240 months. The only data of importance to this study was the asphalt layer rutting data. The critical rutting level is at 0.25 inch. The following table summarizes the data for the four analyses:

Table 1: Rutting Data for X years (this value of X should be the same)

City	Rut depth, inch in X years
Portland	0.184
Chicago	0.185
Raleigh	0.241
Houston	0.276

As can be seen from the table, as one moves further south towards Houston, Texas (towards a higher temperature region), the amount of rutting increases significantly. In fact, the maximum value of 0.25 for SubTotalAC is reached at 203 months in Texas, where the maximum

value is not reached during a span of 240 months for the other three cities. Along with this data

and numerous other sources, it can be observed that the lower a pavement's temperature is

during the year the longer it will survive without needing maintenance.

The results of the MEPDG analysis can be found in Appendix B.

III   Methods and Findings

This chapter will explain in detail how all of the necessary databases and excel files used to design our piping system were created. The first step of this project focused on creating a database of all available types of piping that could be used as the heat exchanger for the Smart Pavement. Next, a variety of excel spreadsheets were created with the ability to allow a user to input either a desired outflow temperature or a desired pipe length and get the necessary output information; a required length or an outflow temperature, respectively. The excel files were created in such a way so that a Smart Pavement could be designed for any parking lot, not just the Kaven Hall parking lot. The Methods and Findings Chapter also explains the temperature testing that was conducted in the Kaven Hall parking lot on the Worcester Polytechnic Institute (WPI) campus, and how the temperature data collected for the area was used to help with the final design of the Smart Pavement.

III.1   Designing the Database

The first major task of the project was to create a Microsoft Excel database that contained all the necessary piping information we needed for the remainder of our work. To complete the database, it required numerous online databases, catalogs and similar resources to gather the following information (items with * will be explained below):

- Type of Pipe (ex: Plastic, Copper, Aluminum, etc.)*
- Alloy Number (if applicable)*
- Hardness*
- Tensile Strength*
- Yield Strength*
- Compressive Strength*
- Elongation
- Density
- Thermal Conductivity*
- Whether the pipe was available in soft or hard tubing*
- Cost/Foot*
- Shear Strength*

- Fatigue Strength*
- Practicality of the Material*
- Link to where information was found*
- Chemical Composition
- Modulus of Elasticity

Many of these properties were found on websites that included online catalogs for all available pipes or on websites that had listing of the physical properties of certain materials. Using the online catalogs and listings, it was possible to find information such as the cost per foot, the alloy numbers of available pipes, and also some of the physical properties of the pipes. However, many properties, such as thermal conductivity and strength, were not able to be found anywhere.

Once the database was completed, however, it was apparent that it was too complicated to be used for the report. Some pipes had much more information than others, and there was too much information included for some pipes which in reality was irrelevant to the scope of this project. To fix this problem, a new database was created, which was called the "Master List" (see Appendix C). This Master List was to be used as the presentable database, and was to be more organized and only contain relevant information. The information that is included in the Master List is indicated above; all items listed above followed by an asterisk were included in the Master List.

It is necessary to note that while the Master List is called final, the database is a document that will need to be continuously improved. Some materials are missing relevant information and some pipes have not been entered due to a lack of any necessary information. For example, graphite piping was brought up as a possible type of pipe to be considered for this work but there is currently no appropriate graphite piping available on the market, thus there is no public information about that type of piping. As graphite pipes become more readily available and more research is done on their strength and thermodynamic properties, the necessary information should be added to the database and Master List and graphite piping should be considered as an alternative choice for the heat exchanger.

After the Master List was created, it was necessary to create spreadsheets which would allow us to quickly calculate certain variables, such as Reynolds number, Outflow Temperature

and Pipe Length. Other useful values to be calculated were the total cost of the system and the amount of heated liquid that could be produced using the given flow rate. The procedure for creating and using the spreadsheets is explained below.

III.2   Computing Necessary Variables

Microsoft Excel was deemed the appropriate program to use when creating the design spreadsheets which would be used to determine the unknown variables needed for the final design of the piping system.   The first thing needed was a spreadsheet which could calculate all the necessary preliminary variables for any given liquid and pipe. The necessary information which would need to be known to continue on in the design would be the local heat transfer coefficient, $\bar{h}$, and the Reynolds number, Re. The Reynolds number is used to determine the characteristic of a liquid's flow and depending on its value, it is determined as laminar flow or turbulent flow. The importance of these flow types is explained later in the report. Below, in Equation 5, is the equation for Reynolds number. Figure 3 shows a flowchart of how to calculate Reynolds number.

$$Re = \frac{\rho v d}{u}$$ (5)

Find Reynolds Number
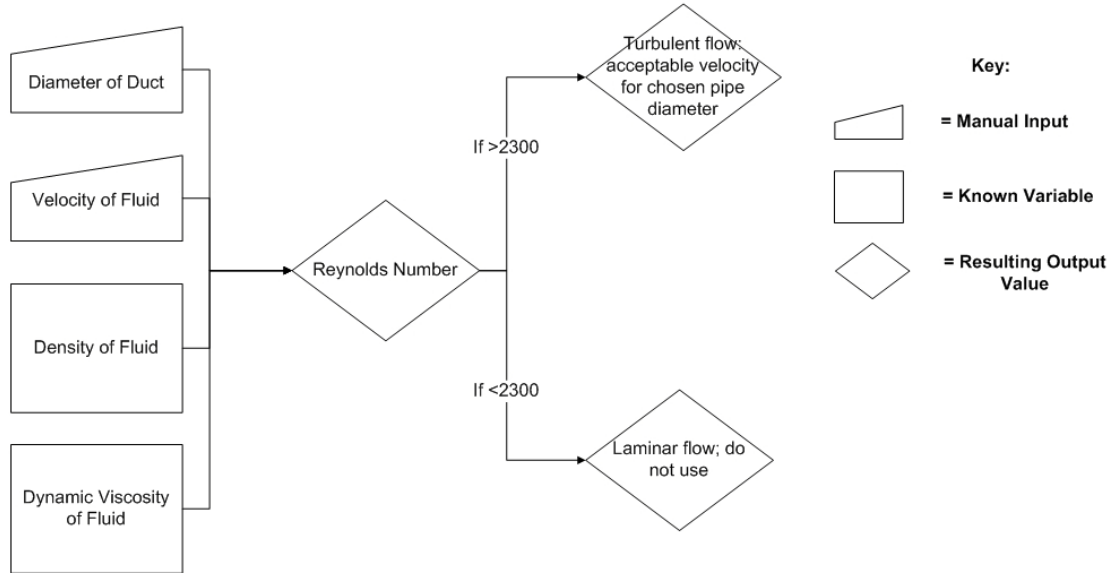
Figure 3: Flow Chart of finding Reynolds Number

Next, a spreadsheet was made which could calculate an outflow temperature for any given pipe and liquid by inputting the length of pipe and the corresponding liquid properties. Then finally, a spreadsheet was created which would function as the alternative to the previously mentioned spreadsheet, and would allow the user to input the desired outflow temperature and receive the calculated value for the required amount of pipe. The two alternative spreadsheets were designed with the thought that while some parking lots may be very small it would be necessary to determine if there was enough space to have the system reach the desired outflow temperature. However, larger parking lots may have plenty of space for the system to achieve the desired outflow temperature so only the exact length needed could be calculated. The specific procedure of how the two spreadsheets were designed and then instructions on how to use them is explained in the next section.

III.3   Determining Outflow Temperature

In order to design a hypothetical system for the Kaven Hall Parking Lot, a method for determining the outflow temperature of the liquid was needed. In order to do this, equations using the principles of thermodynamics were identified and an excel spreadsheet was created so that all information could be easily input into the formula and an outflow temperature could easily be acquired.

When identifying what equation to use from thermodynamic principles, two situations were considered as possible phenomena in our piping system; uniform wall temperature and uniform heat flux. Because the heat flux equation had too many unknown parameters in order to calculate the necessary length of pipe and was also too advanced for our knowledge of thermodynamics, we chose to assume uniform wall temperature. Please see the Recommendations Chapter of the report for more information regarding the uniform heat flux equations.

The equation assuming uniform wall temperature is shown below as Equation 6.

$$\frac{T_w - T_b}{T_w - T_i} = \exp\left(-\frac{\bar{h}A}{\dot{m}C_p}\right) \tag{6}$$

Where T_w is the wall temperature, T_b is the outflow temperature, T_i is the inflow temperature, $\bar{h}$ is the local heat transfer coefficient, A is the surface contact area, $\dot{m}$ is the mass flow rate, and C_p is the heat capacity.

The wall temperature T_w, is the temperature of the pipe wall, which was assumed to be constant at 50°C. This was just an assumed value based on ideal conditions of the pipe having a constant temperature throughout the heating. Later in the course of the project and in the final design, the final wall temperature was changed based on the temperature values for the Worcester area. The outflow temperature T_b, is the temperature of the fluid that leaves the system after going through the piping. The inflow temperature T_i, is the temperature of the fluid at which it enters the piping system. The local heat transfer coefficient $\bar{h}$, is based on the Nusselt number, thermal conductivity of the fluid, and the diameter of the pipe. The Nusselt

number is defined as "as the ratio of convection heat transfer to fluid conduction heat

transfer."[18] The typical Nusselt number for fully developed flow for uniform heat flux and

uniform wall temperature are 4.36 and 3.66 respectively. The surface contact area, A, is the

circumference of the pipe multiplied by the length of the pipe. The mass flow rate, $\dot{m}$, is based

on the velocity of the liquid, the cross sectional area of the pipe, and the density of the fluid.

The heat capacity, C_p, of the fluid is kept constant.

Solving for T_b (or outflow temperature) in Equation 6 is rather difficult to use in a

spreadsheet, especially because of the division of terms surrounding the desired output. So the

equation was rearranged so that T_b could be found more easily. This equation is shown below

in Equation 7.

$$T_b = -exp\left[-\frac{\bar{h}A}{m\,C_p}\right](T_w - T_i) + T_w \qquad\qquad (7)$$

Using this excel spreadsheet, as long as the necessary variables are known for a liquid, a

pipe length could be input into the equation and a resulting outflow temperature, T_b, could be

discovered. The terms of Equations 7 are identified in the previous section. The method of

creating the spreadsheet to calculate our values can be seen in Figure 4.

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[18] http://www.jhu.edu/~virtlab/heat/nusselt/nusselt.htm

Situation #1: Finding Exit Temperature acquired for certain length of pipe
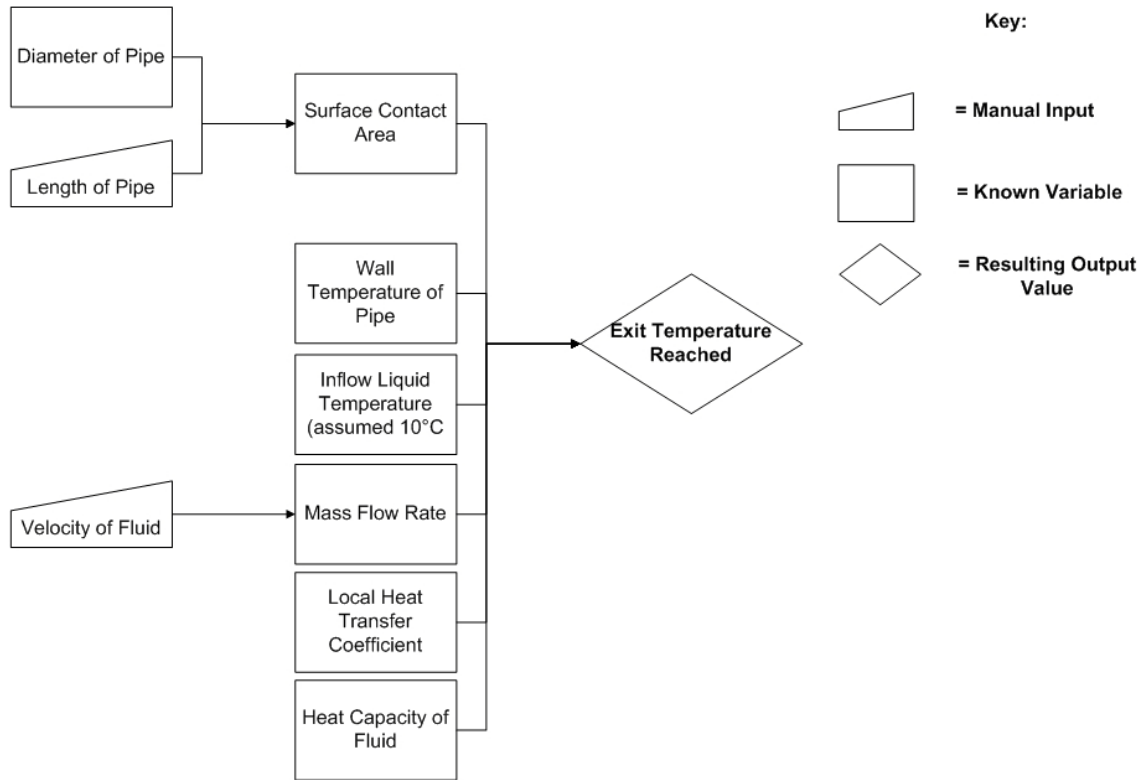
Figure 4: Flow Chart of Tb based on L

After the creation of this excel spreadsheet, named Exit Temperature Calculations, it was evident that another spreadsheet would need to be created to enable the choice of being able to calculate the necessary length of pipe in order to achieve a target outflow temperature. This spreadsheet is explained in the next section. A schematic of the pipe is shown below in Figure 5.
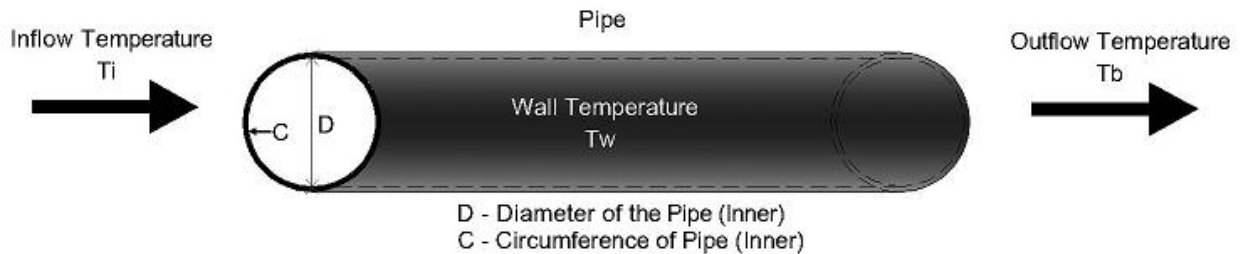
Figure 5: Pipe Schematic

III.4   Determining the Length of Pipe

The alternate spreadsheet for our project involved creating a spreadsheet which would allow an outflow temperature to be input into Equation 8 (below) and a required length of pipe to be the output value. This was done by rearranging the above equation, Equation 7, so that the output value was the variable A (surface contact area), and then dividing A by the circumference of the pipe, C. This resulted in the necessary length of pipe to acquire the desired outflow temperature. The flow chart of how to isolate for the exit temperature can be seen in Figure 6.

$$l = \frac{A}{C} = \frac{-\left[\ln\left(\frac{T_w - T_b}{T_w - T_i}\right)\right]\dot{m}\,C_p}{h\,d} \qquad\qquad (8)$$

Figure 6: Flow Chart of L based on Tb

It is important to note that in this equation, the outflow temperature cannot equal the

wall temperature of the pipe. If this occurs, the equation will not produce an output value because the natural log term will be equal to zero, which is not possible. This makes logical sense, however, as it would be impossible to create a system which lost no energy during the transfer of heat.
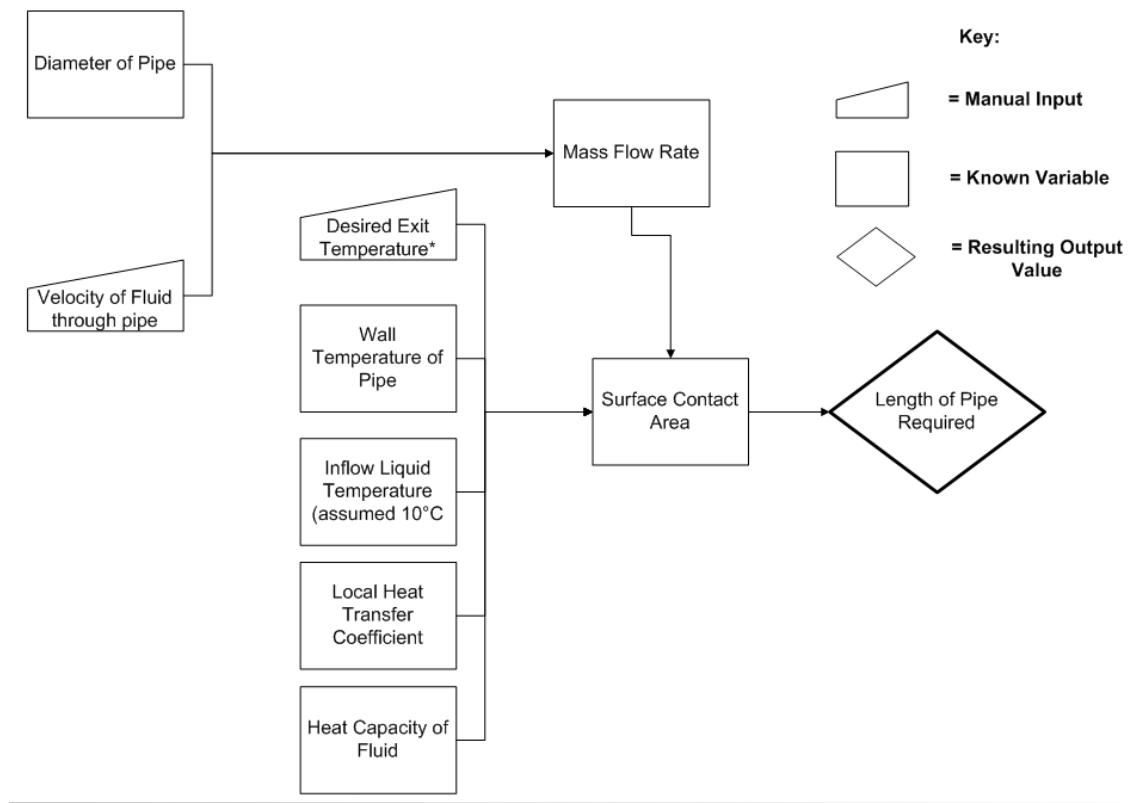
III.5   *Importance of Spreadsheets*

The importance of the spreadsheets created for this project should not be overlooked. For any given parking lot area, a piping system can be designed with just a few quick inputs into the excel files. If an architect or engineer is attempting to design a Smart Pavement for a parking lot with a length of four hundred feet and a width of 300 feet, then they must only determine how much piping could be laid down in that area. Once that is determined, they can choose their pipe size and input that into the spreadsheets. They can then either choose to pick a desired outflow temperature or a target length of pipe and their design will be complete. With the ease of use provided by the design spreadsheets, it is believed that the research conducted by the project team can easily be carried over to future projects.

III.6   *Temperature Testing*

In order to better understand the surface temperature of the pavement in the Kaven Hall parking lot, temperature testing was conducted at the start of the project. This was to ensure the project team and the advisors that the pavement's surface temperature was indeed much higher than the surrounding air temperature. It was also believed that the temperature of the pavement would be much higher in areas exposed to sunlight than those blocked by either shade or parked vehicles throughout the day. The temperature readings were taken in the parking lot that is located outside of Kaven Hall and the Gordon Library at WPI.   A temperature gun was used, which read temperatures in Celsius. Readings were taken on two different sections of the parking lot; Section A and Section B of the parking lot can be seen in Figure 8.

The first day of performing the test was on 10/08/2008 from 12:00pm-12:30pm and

took place in Section A of the parking lot. The outside temperature was approximately 63° F, or 17°C; the weather was mostly sunny with little to no clouds. The recorded temperature at each location in the parking lot was measured using the temperature gun and was then sketched on a printout of Section A. The surface temperature of the pavement ranged from 14 – 36°C. To interpret the data more thoroughly, the raw field data was compiled into an excel sheet and a temperature graph of the parking lot was created, shown below in Figure 7.

It can be seen from the plot that the pavement temperatures were much higher than the outside air temperature. While the air temperature was only 17°C, the highest recorded pavement temperature was 36°C, which is represented by the blue tip. This data proves that the findings of the WisDOT study, that the surface temperature of a pavement is higher than the surrounding air temperature, are true. It also shows that their findings may be underestimating the true temperature of the pavement; using the equations given by WisDOT, the calculated temperatures of the pavement were much lower than some of the recorded temperatures. The average temperature of the pavement was found to be between 26°C and 27°C. This corresponds closely with the WisDot findings, where an air temperature of 17°C will yield a pavement temperature of 24°C. However, our field data suggests that the WisDOT equations may underestimate the pavement temperature as our data shows on more than one occasion surface temperatures above 30°C.
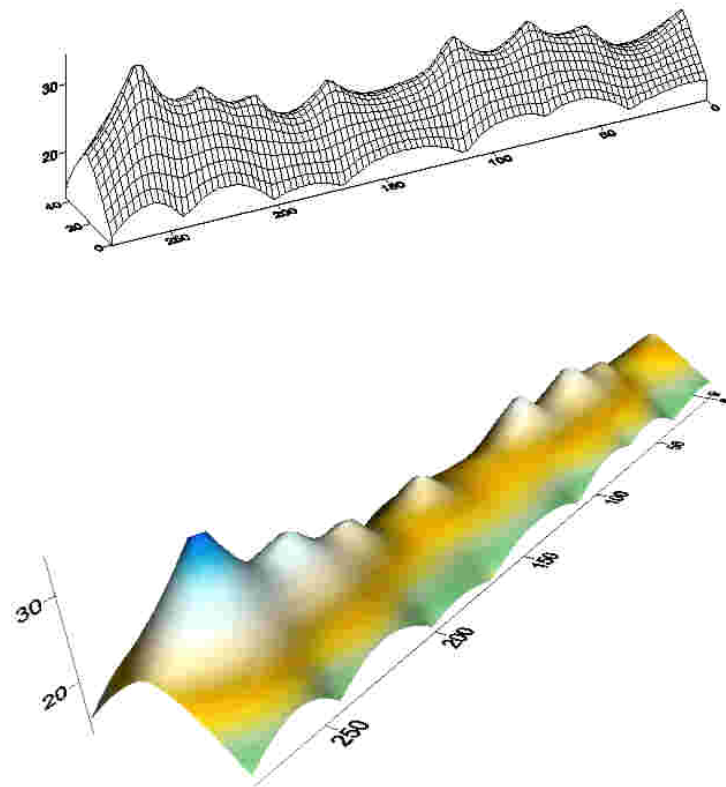
Figure 7: Temperatures of Kaven Hall Lot

Days later, the temperatures were measured for Section B of the parking lot, which is the right hand side of the parking lot (or the west side) when looking at Figure 8 below. Section B is shown as the green section. This temperature test was performed on 10/10/2008 from 2:30pm-3:00pm and the outside temperature was approximately 68° F, or 20°C. For this test, a more structured grid of the parking lot was formed and a reading was taken at each point of the grid. The first point was at point (0, 0), which was the lowest left-hand corner section of the parking lot being studied. Readings were taken every five feet along the grid. To interpret the data more thoroughly, the raw field data was compiled into an excel sheet and a temperature graph of the parking lot was created, shown below in Figure 9.

Figure 8: Kaven Hall Parking Lot Sides A and B

Figure 9: Temperature Graph

It was known previously that the outside air temperature and the amount of solar radiation affect the temperature of the pavement. This phenomenon was presented in the WisDOT study and was also discussed in reports performed by WPI students. The temperature tests conducted in the Kaven Hall parking lot confirm this phenomenon. An interesting finding during the testing was that the black tar used to 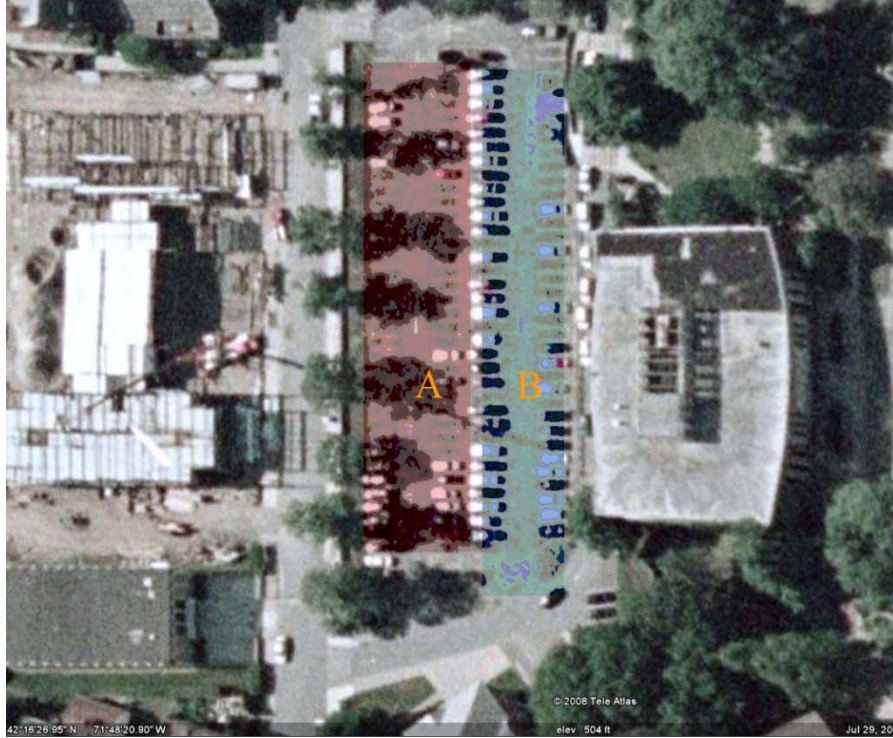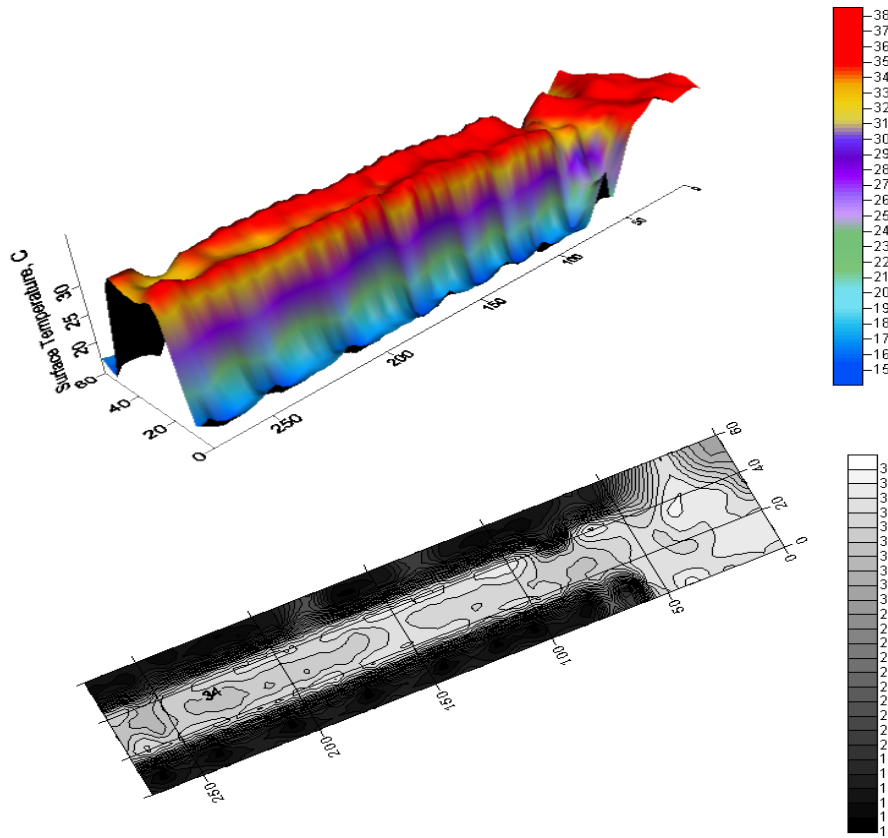fill the spaces where the pavement had cracked had much higher temperatures than the surrounding pavement. This finding was similar to the previous research undertaken at WPI where students and professors experimented with the thermal conductivity of pavement to attempt to either make the pavement absorb more heat or reflect more sunlight. As expected, darker pavements were found to absorb more heat and lighter pavements reflect more heat.

As predicted, the areas of the pavement that remains in direct sunlight have higher surface temperatures. The surface temperatures of the pavement in shaded areas, such as areas beneath parked cars and blocked by nearby trees, are much lower. Temperatures recorded on areas in direct sunlight were as high as 38°C, and areas in the shade were recorded as low as 14°C. This brought about the issue of whether or not piping should be placed beneath the areas of the pavement where the surface temperature would be at a constant low value. For instance, some areas blocked by the shadow of a tree would not always be in the shade because of the sun's movement. However, a parking spot can be assumed to always be in the shade, because on any given day the spot can be occupied by a car for the duration of the day, thus resulting in a low temperature. Because of this issue, it was decided that piping would only be placed on areas of the pavement where cars would not be parking; this accounts for roughly 45% of the pavement's surface. The only areas that will have piping under them are the areas where cars would be driving, such as the entrance and exits and the lanes which lead to the parking spaces.

III.7   Determining Local Temperatures using NOAA

To determine the local temperature for any given area, one may use the NOAA website, located at http://cdo.ncdc.noaa.gov/qclcd/QCLCD. NOAA stands for National Oceanic and

Atmospheric Administration, and they provide the service for free for researchers. This website

allows a user to choose a local weather station and then obtain weather files for certain parts of

the year. Data can be obtained for any given year, month, week or day, and can even be

provided on an hour by hour breakdown. For this report, hour by hour data was acquired for

the Worcester area. In order to find the temperature at certain depths of the pavement, the air

temperatures for the target parking lot, located at the WPI campus in Worcester, MA, needed to

be known. The air temperatures for the nearest weather station to the parking lot were used.

Since the summer months are warmer than the winter months, weather data was compiled for

the months of June, July, August and September. The data is presented in Table 2.

Table 2: NOAA Weather Data for Worcester, MA (2008)

DAY OF MONTH	JUNE $T_{DAILY(MAX)}$, ^{o}C	JULY $T_{DAILY(MAX)}$ ^{o}C	AUGUST $T_{DAILY(MAX)}$ ^{o}C	SEPTEMBER $T_{DAILY(MAX)}$ ^{o}C
1	23.89	27.78	27.78	27.22
2	23.89	25.56	25.56	27.22
3	27.22	28.33	25.56	26.11
4	17.78	19.44	25.56	28.33
5	15.00	20.00	23.33	29.44
6	15.00	25.56	19.44	26.67
7	31.67	27.78	25.00	23.89
8	31.67	30.00	23.89	23.33
9	33.33	29.44	24.44	21.11
10	34.44	25.56	25.56	19.44
11	26.67	25.56	18.89	20.00
12	25.00	26.11	22.22	18.33
13	26.11	26.67	24.44	23.33
14	27.78	24.44	24.44	23.33
15	17.78	27.78	25.00	24.44
16	19.44	28.89	25.00	18.89
17	22.22	29.44	26.11	21.11
18	20.00	31.11	28.33	19.44
19	21.67	32.22	23.89	15.56
20	22.78	31.11	21.11	18.33
21	25.56	28.89	25.00	25.00
22	25.00	25.00	27.22	16.11
23	21.11	20.56	26.11	18.89
24	23.89	24.44	26.11	19.44
25	25.56	27.22	26.11	18.33
26	22.78	28.33	22.22	16.11
27	28.33	25.56	24.44	18.33
28	22.78	26.67	25.00	22.22
29	30.00	27.78	24.44	20.56
30	27.22	27.78	24.44	18.33
31	x	28.33	25.56	x

ALL TEMPERATURE DATA COLLECTED FROM http://cdo.ncdc.noaa.gov/qclcd/QCLCD

III.8   *Finding the Temperature of the Pavement*

In order to find the approximate temperature of the pavement at 1.5" below the surface, the WisDOT equations were used in conjunction with the above data. Equation 4, shown below, from the WisDOT study was used to calculate the maximum daily temperature for each day in the months of June, July, August, and September. The maximum temperatures under the pavement are summarized in Table 3.

Table 3: Temperature below pavement based on WisDOT equations for Worcester, MA (2008)

DAY OF MONTH	JUNE	JULY	AUGUST	SEPTEMBER
	$T_{PAV @ 6.4MM(MAX)}$ °C	$T_{PAV @ 6.4MM(MAX)}$ °C	$T_{PAV @ 6.4MM(MAX)}$ °C	$T_{PAV @ 6.4MM(MAX)}$ °C
1	31.24	35.47	35.47	34.86
2	31.24	33.05	33.05	34.86
3	34.86	36.07	33.05	33.65
4	24.60	26.41	33.05	36.07
5	21.58	27.01	30.63	37.28
6	21.58	33.05	26.41	34.26
7	39.69	35.47	32.45	31.24
8	39.69	37.88	31.24	30.63
9	41.50	37.28	31.84	28.22
10	42.71	33.05	33.05	26.41
11	34.26	33.05	25.80	27.01
12	32.45	33.65	29.43	25.20
13	33.65	34.26	31.84	30.63
14	35.47	31.84	31.84	30.63
15	24.60	35.47	32.45	31.84
16	26.41	36.67	32.45	25.80
17	29.43	37.28	33.65	28.22
18	27.01	39.09	36.07	26.41
19	28.82	40.30	31.24	22.18
20	30.03	39.09	28.22	25.20
21	33.05	36.67	32.45	32.45
22	32.45	32.45	34.86	22.78
23	28.22	27.61	33.65	25.80
24	31.24	31.84	33.65	26.41
25	33.05	34.86	33.65	25.20
26	30.03	36.07	29.43	22.78
27	36.07	33.05	31.84	25.20
28	30.03	34.26	32.45	29.43
29	37.88	35.47	31.84	27.61
30	34.86	35.47	31.84	25.20
31	x	36.07	33.05	x

This shows that the temperature within the pavement is greater than the surface air temperature. For example, on June 1, 2008, the maximum surface air temperature was 23.89°C which resulted in a temperature below the surface of 31.24°C.

However, it can be seen that the values that resulted from the equation contradict the values that were found from the temperature testing of the surface. When testing Section A of the parking lot, the outside air temperature was about 63°F or 17.2°C, and pavement temperatures range from 23°C to 36°C (which does not include the area in the shade). However, when the 17.2°C air temperature is inputted into the WisDOT Equation 4, it resulted in the maximum value of 24°C. Although it is a comparison between two different situations, there should not be a difference of 12°C between the maximum measured temperature at the surface of 36°C and the maximum calculated temperature at 6.4mm below the surface of 24°C. This can be explained however as the 36°C surface temperature was measured above a small section of black tar in the WPI parking lot. So the temperatures are actually similar.

IV   Design of the Smart Pavement

This Chapter will present the final design for the Smart Pavement. The materials to be used will be identified and reasons for why they were chosen over alternative materials are given. The designs for the heat exchanger and the liquid to be used will also be presented.

IV.1   Choosing a Pipe

The first step in the design of the pavement system was to choose a final design for the pipe. The variables that needed to be decided upon were what material would be used, such as copper, plastic, aluminum, etc. what size the pipe would be, and where the pipe would be placed in the pavement. The pipe size was the first parameter to be chosen for because the material of the pipe could be determined later on. The following section describes how the size of the pipe was chosen.

IV.1.1 Determining Pipe Size

From previous research it was known that the pipes should be buried so that the top of the pipe would be 1.5 inches below the surface of the pavement[19]. A cross section of a pavement with the pipes in place can be seen below in Figure 10. At this depth, the pipe would be able to support all of the potential forces that would occur in a parking lot, such as the force of a truck driving over it, while still be close enough to the surface for any necessary maintenance. Also, during field testing by previous researchers, including WisDOT, it was found that at this depth, pavement is as hot as, if not hotter, than the surface temperature of the pavement[20]. Because the pipes would be buried so that the top of the pipe would be 1.5 inches below the ground, smaller pipes were researched to ensure that the bottom of the buried pipe

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[19] Chen, Bhowmick, and Mallick. (2008). Harvesting Energy from Asphalt Pavements and Reducing the Heat Island Effect
[20] Peter J. Bosscher, Hussain U. Bahia, Suwitho Thomas, and Jeffrey S. Russell. (1998). Relationship between pavement temperature and weather data. *Transportation Research Record, 1609*

would not be too deep into the pavement, thus not taking full advantage of the hottest area of

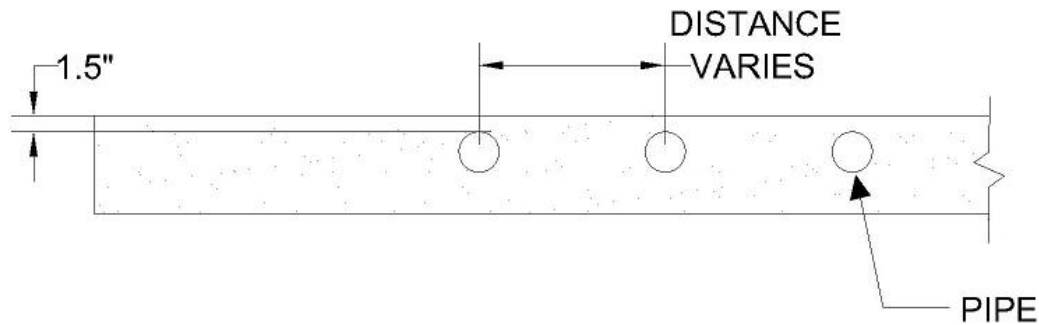the pavement and making any maintenance extremely costly.

Figure 10: Typical Cross Section of a Smart Pavement

Knowing that the pipe would be buried 1.5" from the surface, the next step was to

determine what size the pipe would be. Due to the fact that most pipes found in catalogs came

in certain sizes, such as ¾", 1 ½", 2", etc., the choices for what size to make the pipes was limited

to only pipe sizes that could be found in catalogs. Another factor in determining pipe size was

matching the chosen pipe size to the size of existing domestic water lines so if a connection

between the water line and the underground piping were to occur it would be feasible. If the

pipe size chosen was too big or too small and it was connected to the domestic water line, then

either the system would not be able to handle the normal flow rate of the water lines or would

be unnecessarily large. Domestic water lines are typically ¾" to 1 ½" in diameter. Knowing this

the design was limited to those two diameters.

Other things considered for pipe size were the potential volumetric flow rates and the

length that would be required to heat a liquid to a desired temperature. Again, smaller pipes

were found to be better choices for almost every aspect. While the flow rate can be larger in a

4 inch pipe compared to a 2 inch pipe, a 2 inch pipe will be able to heat any given amount of

water much faster than a 4 inch pipe. This trend points towards using a pipe size of either ¾

inches or 1 ½ inches. However, because more volume can be obtained from a system using 1 ½

piping compared to ¾ inch piping, 1 ½ inches was chosen to be the design size.

IV.1.2 Material of the Pipe

The final step in the pipe design was choosing a material. While numerous materials were researched, one material, copper, came out as being ideal for the design of the underground piping system, specifically from the viewpoint of thermal conductivity. Table 4 shows the summarized data we used to determine which material the pipe would be made of.

Table 4: Comparison of Materials

Type of Pipe	Thermal Conductivity* (W-m/K)	Cost/Foot** ($)	Yield Strength* (psi)
Aluminum	180.00	1.26	47,000.00
Polyethylene (Plastic)	0.29	6.49	3,200.00
PVC (Plastic)	0.05	1.32	7,500.00
ABS (Plastic)	0.33	17.66	6,400.00
Copper	401.00	0.32	120,000.00
Rubber	3.00	2.57	1,000.00
Graphite	470.00	***	***
*The highest value for the corresponding material is shown			
**The lowest value for the corresponding material is shown			
***Information still unknown			

Thermal conductivity was one of the main points of interest to be examined for each material. This was due to the fact that an efficient transfer of thermal energy from the pavement into the pipe was desired. This would allow for the liquid in the pipe to be easily heated by the piping system. While graphite has the highest thermal conductivity, there are currently no available commercial pipes made from graphite. Therefore, copper was chosen as the best thermal conductor out of the available materials.

Providing a system that saved money in the long run would not factor into the final decision. However, it should be noted that copper pipes also had the lowest cost per foot. Strength was another important factor when deciding what pipe to use. It can be seen here again that, copper had the highest available strength of all the materials.

Overall, copper was far and beyond the best choice available at the current time. No
other material could match its thermal conductivity except graphite, which is still unavailable,
nothing came close in regards to cost per foot and the strength of copper can far exceed the
strength of the other materials. Copper is also a good choice because it is a relatively cheap but
durable material, requires little maintenance and is used widely in construction.

IV.2   *Piping System Design*

The design involves choosing the fluid or gas to run through the pipe, the layout of the
system, and the length of pipe needed. The heat exchanger was chosen to be a copper pipe for
its low cost and high thermal conductivity. There are different types of copper pipes as seen in
the database of pipes. Next, the fluid within the pipe would need to be chosen. After
considering different liquids with different boiling points, the liquid flowing through the pipes
was chosen to be water. Water was the most practical material because it can be used directly
for domestic hot water for a number of uses, including laundry, bathrooms, etc. It would also
be easier to have a system run from the existing utility lines into the Smart Pavement and then
into the building. Since the system is for the WPI parking lot, the adjacent buildings could then
use the heated water. Another proposed system was to use a liquid with a low boiling point to
power an electricity-generating turbine. However, the temperature of the liquid would need to
be above the maximum of 50°C, which cannot be reached in the Worcester area in order for the
turbine to work. Because of this, this idea was discarded, but the idea could possibly work in
other locations.

In both cases, it was assumed that the uniform wall temperature of the pipe would heat
up to 45°C and that we wanted an outflow temperature close to that number. This temperature
was based off the results from the WisDOT paper equations, after inputting the surface
temperatures in Worcester on a typical summer day. An outflow temperature of 44.95°C was
chosen and a system was designed for a 1.5", 2", 3", or 4" diameter pipe. A flow velocity had to
be chosen, which would allow for turbulent flow rather than laminar flow. A flowchart, shown
as Figure 3, is available to explain how the Reynolds number works for turbulent flow versus

laminar flow. It is important to note that when entering values into the spreadsheet there are some very important restrictions on what can be entered. Most importantly, the outflow temperature T_b can never equal or be greater than the wall temperature T_w. For instance, if an outflow temperature of 44.95 °C is desired, there must be a wall temperature that is greater than 44.95°C throughout the system. Also, the outflow temperature should never equal the wall temperature, as mentioned above. On a minor note, setting the outflow temperature equal to the inflow temperature will result in a length of 0, because if the desired temperature for the water has already been reached, then no pipe length is required for the water to increase its temperature.

After leaving the system of pipes, water would go into a reservoir to be heated up to 50°C in case the outflow temperature is not high enough for domestic use.

IV.2.1 Results

After determining the results for the exit temperature of a certain length of pipe, a graph was created to summarize the results. From Figure 10, we can say that a faster flow rate would require a longer length of pipe in order to reach the desired outflow temperature of 44.95°C. A 1.5" pipe with a velocity of 0.0033 ft/s (or 0.001 m/s) would require a length of 15.4 feet, but for a velocity of 0.0066 ft/s (or 0.002 m/s), it would require 30.7 feet of pipe length. Also, the larger the pipe diameter, the greater the length of pipe is needed. For a 2" diameter pipe, it requires a length of 27.3 feet when water flows at 0.001 m/s compared with the 15.4.3 feet for the required for the 1.5" pipe.

As it can be seen, the larger diameter pipe required a greater length of pipe in order to reach its desired exit temperature (which was set to 44.95°C in this example). Figure 11 shows the comparison of the different sized pipes, which confirms our conclusion. It can be seen that the slope of the plot for the smaller sized pipe is greater than the slope of the plot for the larger sized pipe. This means that a smaller pipe has a smaller length of pipe required for a certain flow rate in order for the water to reach the desired exit temperature. However, the table did not include the results which have a laminar flow.
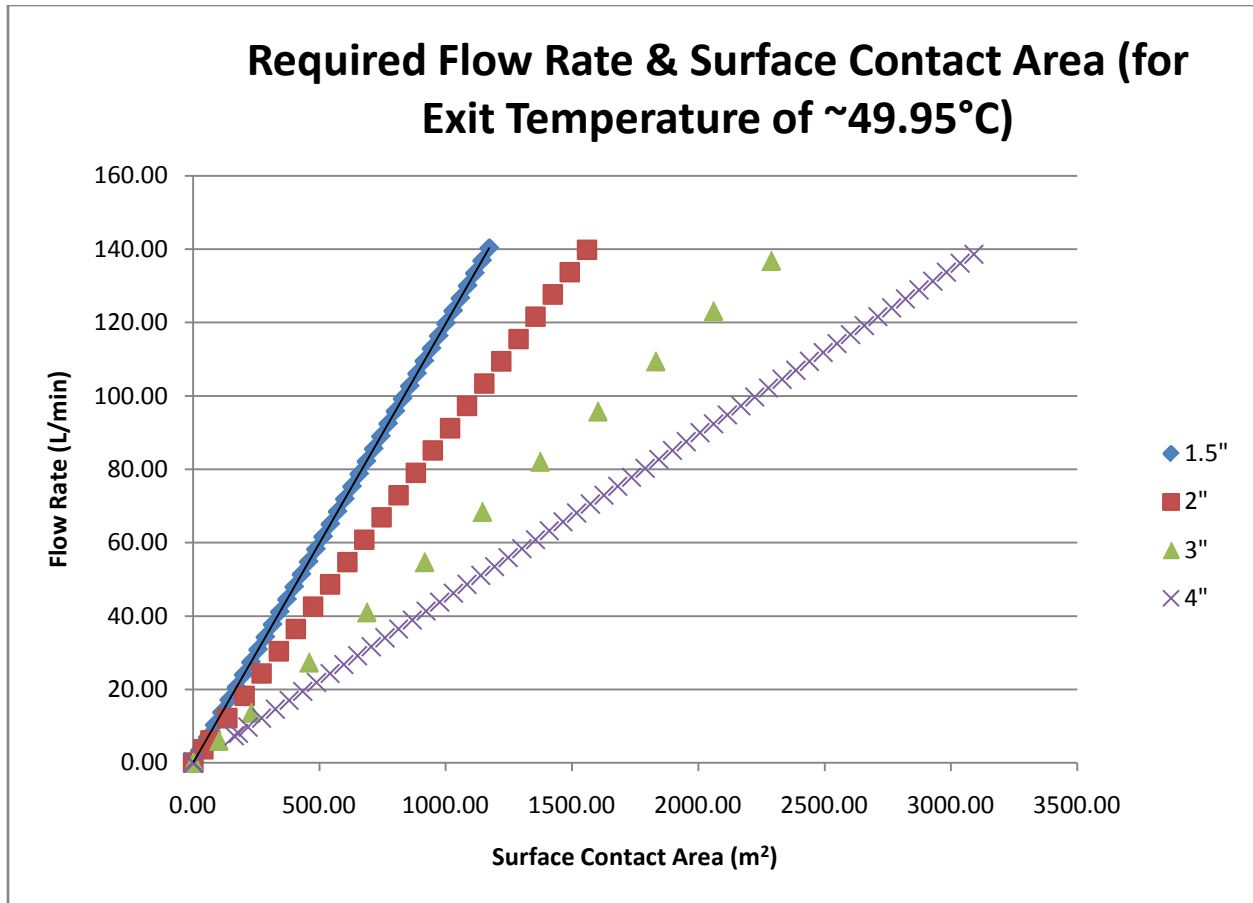
Figure 11: Required Flow Rate @ 49.95°C

Figure 12 shows the individual results for the 1.5 inch pipe. A certain combination of length of pipe and the flow rate of the water yields the desired outflow temperature of the water.

There is a proposed layout of the piping system which would have a length of 2400 feet in length. This length was inputted into the equation where length and the flow rate of the water would yield the exit temperature which can be achieved.
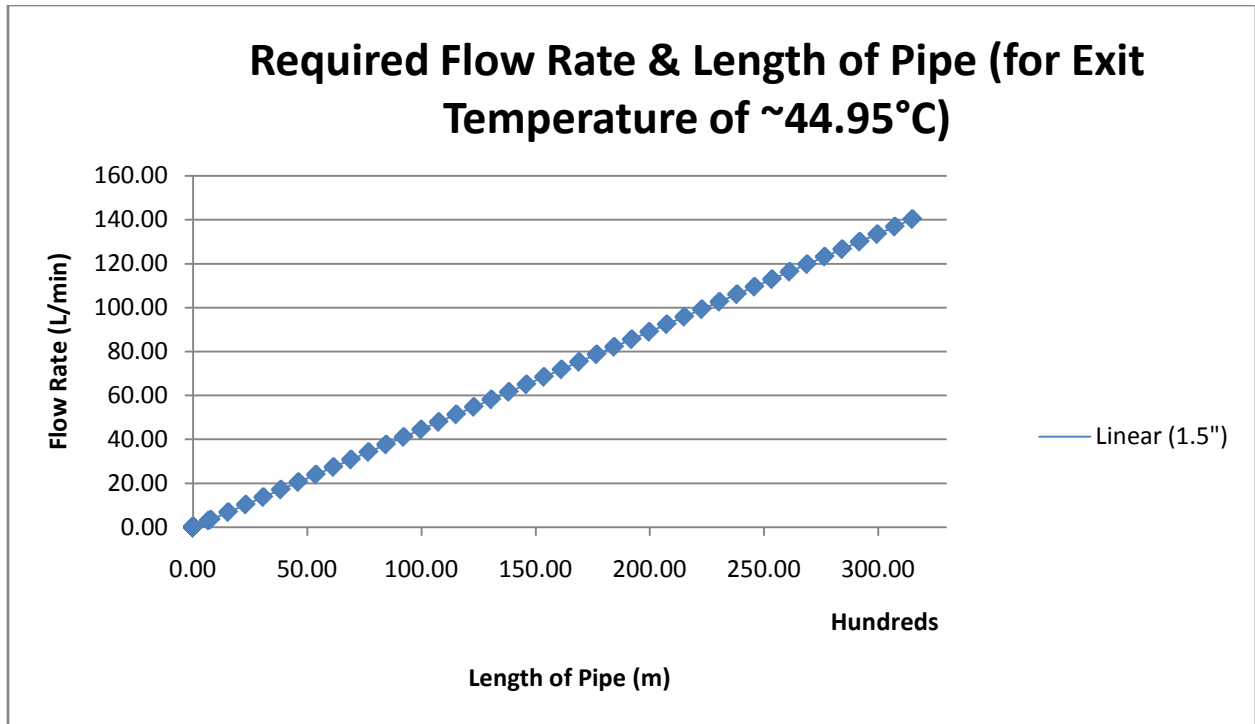
Figure 12: Required Flow Rate and Length of Pipe for 1.5" Pipe

Figure 13 shows the individual results for the 2 inch diameter pipe. Figure 14 shows the results for the 3 inch pipe. Figure 15 shows the results for the 4 inch pipe.
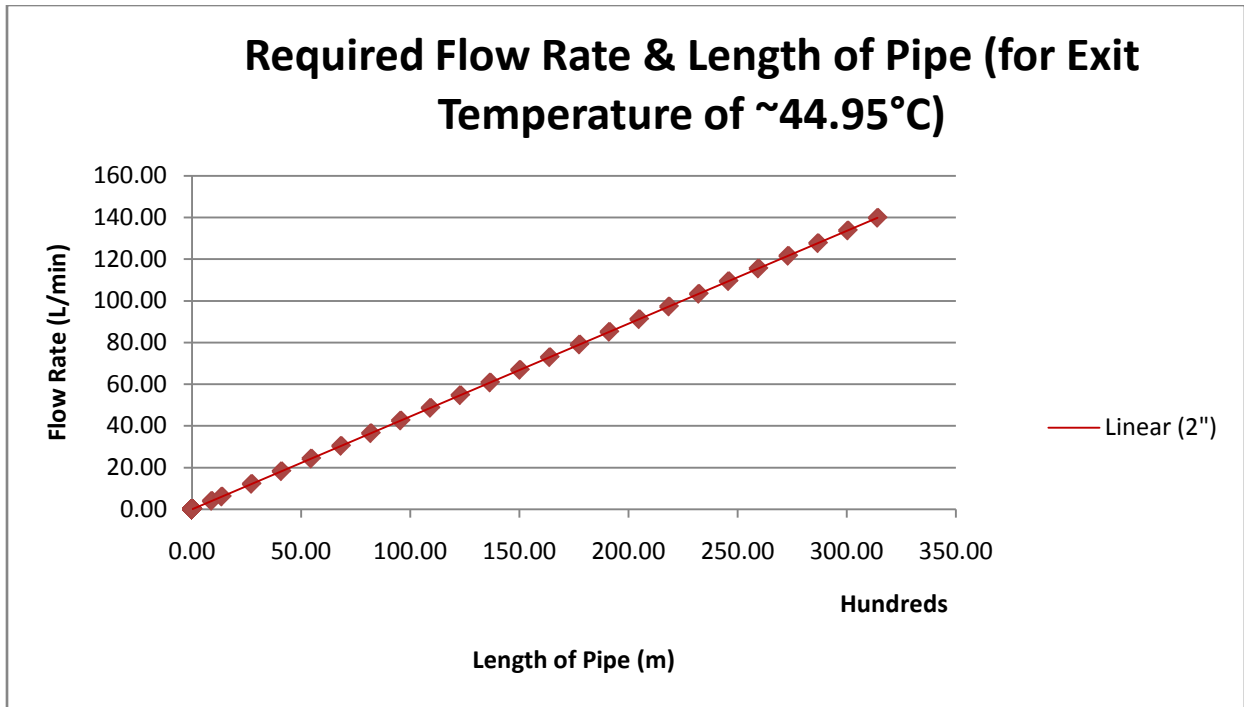
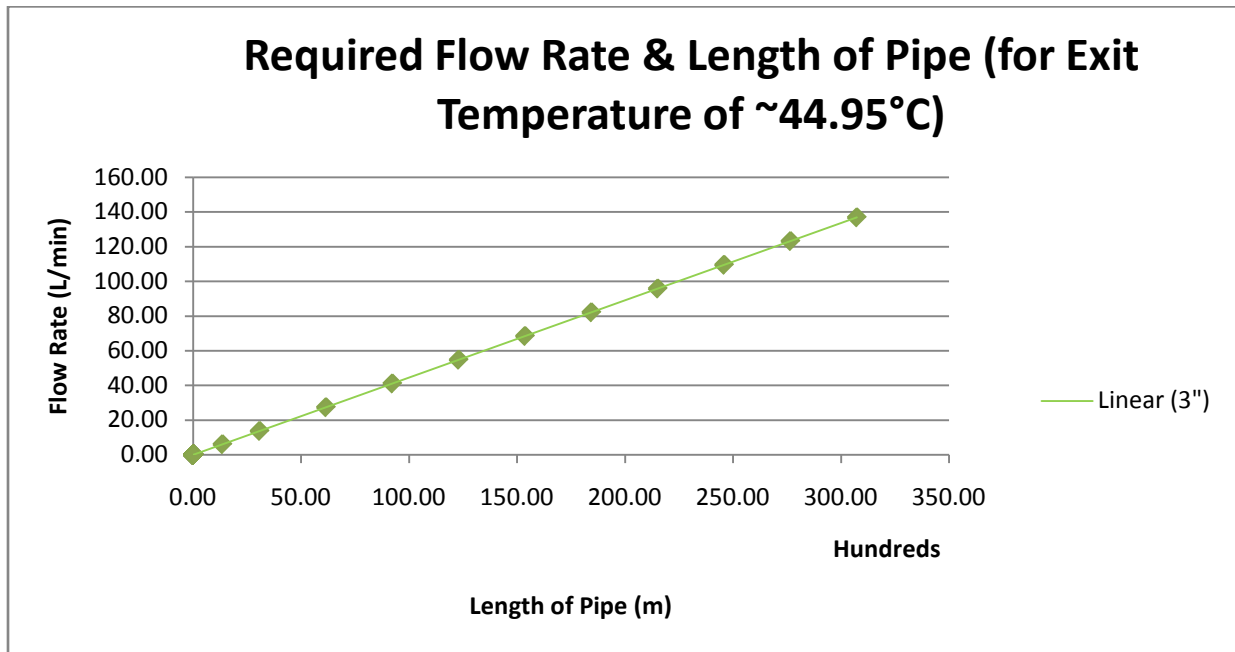**Figure 13: Required Flow Rate and Length of Pipe for 2" Pipe**

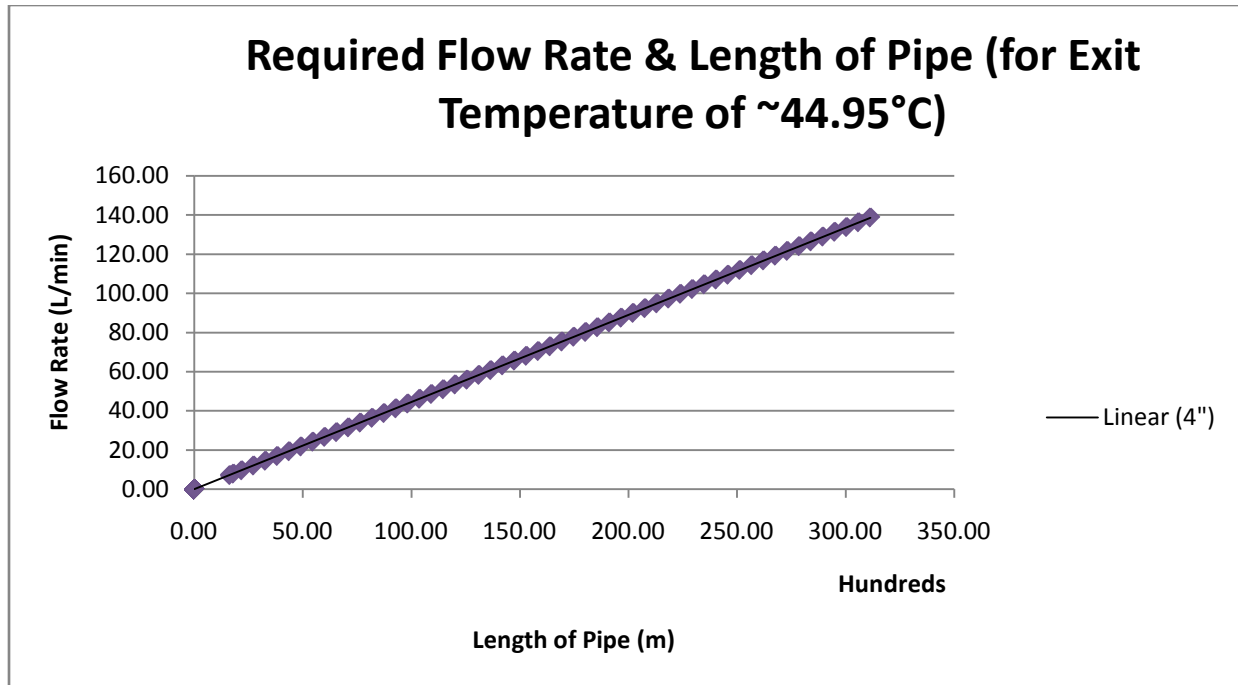**Figure 14: Required Flow Rate and Length of Pipe for 3" Pipe**

Figure 15: Required Flow Rate and Length of Pipe for 4" Pipe

It still needs to be determined whether the copper pipe can reach the assumed temperature of the pavement to be 45°C at 1.5" below the surface of the pavement. Also, this temperature assumes a constant wall temperature. The wall temperature would not necessarily be constant or uniform for a parking lot in reality, especially after some thermal energy being taken away from the pavements.

A major limitation in using this model is that it is based upon ideal conditions where the temperature of the pavement could reach up to 45°C and that it remains constant at 45°C.

One thing to notice is that the relationship between the flow rate and the length of pipe required is linear. For a certain desired exit temperature of water through the pipe, it can be seen that as the flow rate increases, the length of pipe increases as well.

In choosing which pipe size to use, Table 5 summarizes the minimum pipe lengths required for an outflow temperature of 44.95°C that have turbulent flow.

Table 5: Comparison of Pipe Length for Turbulent Flow

Diameter of the Pipe (in)	Exit Temperature (^{o}C) (T_b)	Length of Pipe (ft)	Reynolds Number (Re = pvd / u)	Volumetric Flow Rate (L/min)	Liters of water produced in 4 hours
1.5	44.95	675.9940137	2310.68	3.010	722.362
2	44.95	901.3253516	2310.68	4.013	963.150
3	44.95	1351.988027	2310.68	6.020	1444.724
4	44.95	1802.650703	2310.68	8.026	1926.299

This table shows the amount of piping length required for the 1.5", 2", 3", and 4" pipe. It can be seen that the Reynolds number of 2310 is greater than 2300 so then turbulent flow is achieved. This number means that any flow rate greater than that current situation would still be in turbulent flow. But if the flow rate increases, so would the length of pipe required as previously seen in Figures 9 to 12.

IV.3   Final Design of the Smart Pavement

The following figure (Figure 16) shows the final design for the Smart Pavement to be placed in the Kaven Hall parking lot at the WPI campus.
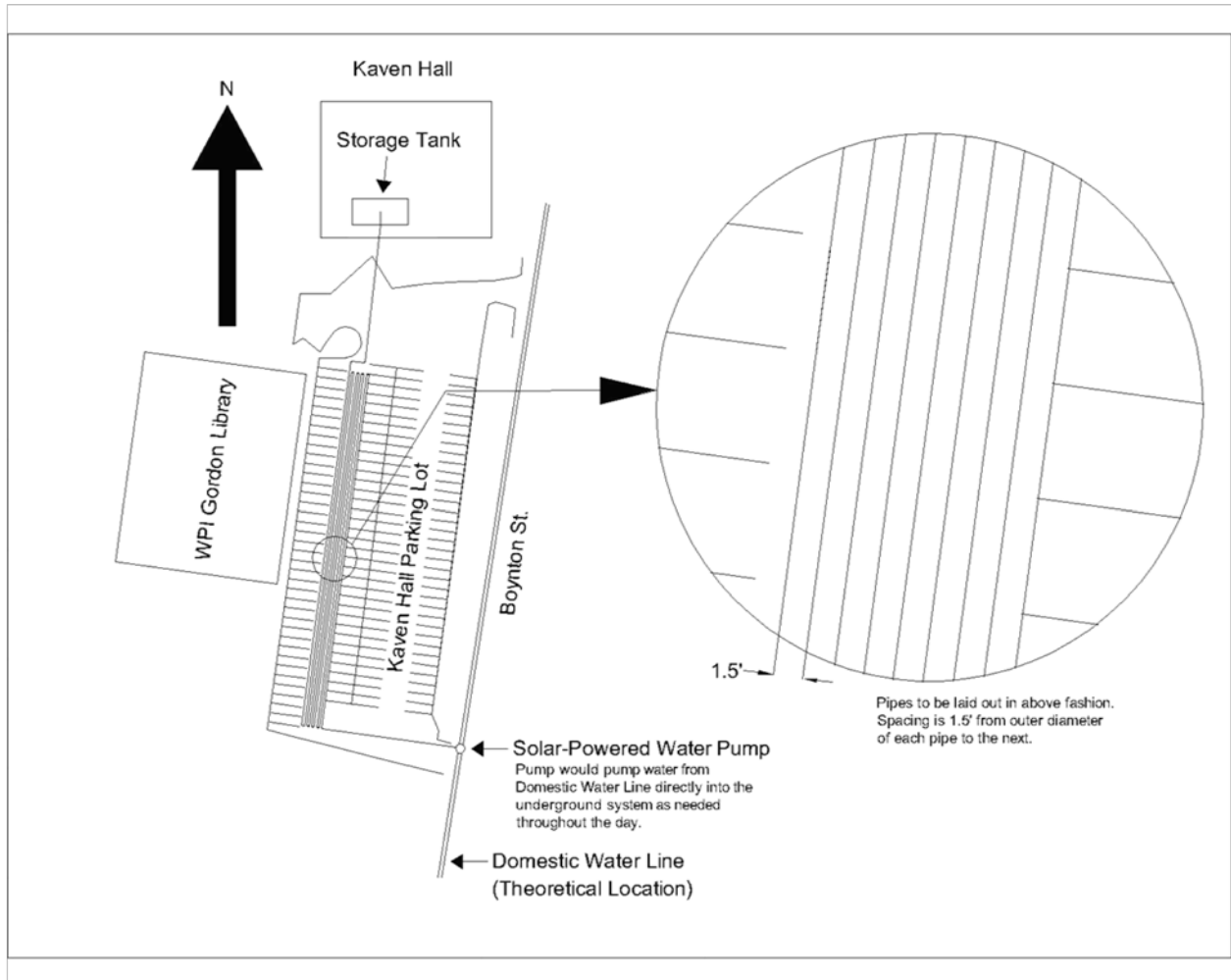
Figure 16: Final Design of Smart Pavement

As can be seen from the Figure, a straight piping strategy was chosen for the final design. This was to allow for the most amount of roadway to be covered by the system but at the same time decreasing the amount of turns in the pipes. The system starts with a hook up to the domestic water line. The locations of the public water lines were unknown so an assumed location is shown. At this connection, a solar powered water pump would be used to pump water throughout the Smart Pavement during the day. The water would then run throughout the system of pipes, collecting the heat energy as it goes through the system. Upon reaching the end of the pipes, the water would enter a storage tank located in the lower floor of Kaven Hall. This storage tank would be able to hold at least the amount of heated water that could be produced by the Smart Pavement on any given day.

The above system can produce up to 240 gallons of water per day using a flow rate of one gallon per minute. Only 240 gallons of water can be produced because the system can only heat water for four hours each day. The amount of piping used can vary depending on how much surface the architect wants to be exposed to running water, but the minimum length of pipe needed is 261 feet. The current system shown has well above the necessary amount of piping, almost 2400 feet.

Using the excel files, the designer can change around the numbers and flow rates for any given Smart Pavement design. The flow rate of the water can change, the target exit temperature can change or even the size of the pipe could be changed using the spreadsheets created for this project.

V   Cost Benefit Analysis

Before using this system, one would need to see if this system would be worth using in the first place. So a comparison, between the regular method of heating water for domestic use and the use the solar energy piping system, needs to be made.

Heating 1 gram water by 1 C requires 4.184 joules.[21]It can be seen in the specific heat capacity of water which has units of kJ/kg°C. Equation 9 shown below can be used to calculate the amount of energy required to heat water to a desired temperature.

$$Q = c_p m \Delta T \hspace{5cm} (9)$$

Where c_p is the specific heat capacity, $m\Delta T$ change in temperature in Kelvin or Celsius.

For the first case without the piping system, the temperature difference would be the typical inflow temperature of water (of 10°C) for the main water pipeline and the desired outflow temperature (of 50°C). Therefore the difference change in temperature would be 40°C. After finding the amount of energy required, the cost can be found by multiplying the energy required with the cost per KWH of $0.1032 which was found off the Energy Information Administration for retail price of commercial customers.[22] The results are shown below:

Table 6 : Cost of Energy without the piping system

Diameter of the Pipe (in)	Volumetric Flow Rate (L/min)	Liters of water produced in 4 hours	kJ* required to heat to 50°C without piping system	Cost of energy without piping system
1.5	3.010	722.362	1.21E+08	$3,463.41
2	4.013	963.150	1.61E+08	$4,617.88
3	6.020	1444.724	2.42E+08	$6,926.81
4	8.026	1926.299	3.22E+08	$9,235.75

If the piping system was to be used, the cost of energy would decrease because the

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[21] The Engineering ToolBox. *Heat, Work and Energy.* http://www.engineeringtoolbox.com/heat_work-energy-d_292.html
[22] Energy Information Administration. Electric Power Monthly-Average Retail Price of Electricity to Ultimate Customers. http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html

system would raise the temperature of the water by a certain amount before it enters the building for use. This way, the temperature difference would be smaller, resulting in less energy usage to heat the water to 50°C. However, the cost of installing and maintenance the piping system needs to be included as well in the end. The cost of pipe is about $0.32 per foot of piping.

Table 7: Cost of Energy with the piping system

Diameter of the Pipe (in)	Length of Pipe (ft)	Cost of Pipe	Liters of water produced in 4 hours	kJ required to heat to 50°C with piping system	Cost of Energy (Commercial) ($/KWH)	Cost of energy with piping system
1.5	675.99	$216.32	722.362	1.53E+07	0.1032	$437.26
2	901.33	$288.42	963.150	2.03E+07	0.1032	$583.01
3	1351.99	$432.64	1444.724	3.05E+07	0.1032	$874.51
4	1802.65	$576.85	1926.299	4.07E+07	0.1032	$1,166.01

It can be seen that the cost of energy is reduced by a factor of nearly 8. So the cost of energy is cut by 8 times the amount, compared to not using the piping system. This is a very significant reduction in cost. However, there are some issues that need to be considered.

The surface temperature of Worcester was based on the highest temperature recorded on the NOAA website in the summer of 2008. So, the temperature of the wall was found using the WisDOT equations. But this high temperature may not always be reached, so it is only based on the most favorable situations. The temperatures of the pipe are mostly lower than this temperature of 45°C. Also using this excel sheet assumes that the wall temperature is exactly the same as the temperature below the surface of the pavement. This is not likely because there is a heat transfer from the pavement to the pipe, which results in an energy loss.

The excel sheet is dependent on uniform wall temperature, and it is very likely that the system in use would not fulfill uniform wall temperature. However, the excel sheet does give an approximate look into how the piping system should be designed.

VI   Recommendations and Alternatives

The Recommendations and Alternatives Chapter will present recommendations that can improve the design of a Smart Pavement either for use on the WPI campus or at another location. The recommendations are based either on the shortcomings of the study or on hypothetical situations that could arise in a parking lot and are meant to guide future research involving harvesting the thermal energy of pavements for residential or commercial use. In some cases, alternative designs or procedures are mentioned that could be used instead of our above mentioned design.

VI.1   Analyze Heat Transfer Using Heat Flux Equations

The piping system, as mentioned in the Methodology chapter, was designed using the assumption that the wall temperature of the pavement would be at a constant value, a concept of heat transfer known as uniform wall temperature. The wall temperature of the pavement that was used in the calculations was based on an equation that was developed by the Wisconsin Department of Transportation (WisDOT). The equations are quite simple, and only require knowing the average air temperature for a given day and how deep into the pavement the desired unknown temperature is[23]. This concept and set of equations made finding the wall temperatures for certain depths below the pavement surface simple and thus it was easy to create a design using the obtained air and pavement temperatures given the system of design spreadsheets.

Unfortunately, uniform wall temperature is an ideal situation, and is likely never to occur in a real-life scenario because of the varying levels of sun exposure on a pavement surface and the effect of parked cars and shade from trees. This can be seen from the temperature testing that was conducted; certain areas of the pavement were over 30°C or even 40°C during the month of October, but other areas, mostly areas that were under parked cars and in the shade,

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[23] C Peter J. Bosscher, Hussain U. Bahia, Suwitho Thomas, and Jeffrey S. Russell. (1998). Relationship between pavement temperature and weather data. *Transportation Research Record, 1609*

were below 17°C. This results in not only having a non-uniform temperature profile on the surface of the pavement, but also at certain depths beneath the surface. Therefore, it is incorrect to assume that uniform wall temperature occurs in a pavement structure.

The alternative concept, constant heat flux, was too complicated to be used by the project group due to a lack of understanding on the subject matter, however, would provide much more realistic calculations to substantiate claims that Smart Pavements are an economically feasible idea. Constant heat flux is a very advanced concept and the large amount of calculations needed to determine the wall temperatures of a pavement would have stalled the progress of the project. However, if a future project team were given one task of calculating these equations, it would be beneficial to the design of the system.

It is recommended that at some point before the actual implementation of the Smart Pavement the heat transfer from the pavement to the liquid be further studied using equations and assumptions derived from the concept of constant heat flux. While the findings for what material and what liquid to be used will most likely still hold as they were chosen based on other considerations, they may not be as efficient of a heat transfer as this study suggests. Any project group that studies this issue will have to have significant background knowledge and coursework in the field of heat transfer or thermodynamics; introductory classes or knowledge in either subject will not provide enough understanding of constant heat flux for a group to calculate the true thermal transfer from the pavement to the liquid.

VI.2   Research Graphite Piping

While copper is a very durable and easy to use construction material, there are other materials that could provide a more efficient transfer of heat from the pavement to the liquid. One such material is graphite, and it is recommended that the possibility of using graphite as opposed to copper for the material of the pipe in the Smart Pavement be researched. While the necessary form of graphite piping was still unavailable for commercial use at the time of this study, early opinions of the use of graphite as a strong thermal conductor seemed very

promising. Companies such as Watts Radiant, who specialize in Interior Floor Heating and Snow-melting, have begun using graphite in their residential heating and snow melting, and have recently completely abandoned aluminum piping in favor of graphite due to its "unique atomic structure [which] enables it to transfer heat more efficiently than aluminum"[24]. If any useable form of graphite piping were to become available that had similar properties to the piping that Watts Radiant is currently using, then it may be more efficient than copper and thus be the wiser choice for the system.

The cost of graphite piping is the biggest issue, however. Since the material is not widely used yet as a construction material, as opposed to copper, it may end up being too expensive to warrant using in the system. Copper already has a very high thermal conductivity, so graphite would need to have an extremely efficient way of transferring the thermal energy of the pavement to the liquid if it were significantly more expensive than copper pipes. As already mentioned though, copper is so cheap compared to other materials that the graphite piping would need to either a) also be cheap or b) be much more efficient than copper so that its usage can be justified from long-term perspective.

VI.3   Beware of Winter Maintenance

Another aspect of the Smart Pavement which was not able to be researched was the effect of cold temperatures on the system. Fears that severely low temperatures could damage the underground pipes or cause any left over water in the system to freeze should be more thoroughly addressed. As of now, the current plan is to only use the system in the warmer months, such as spring and summer time, and then shut it down and drain the excess liquid in the colder months so as to not to risk letting the system freeze and become damaged. However, if the system could be used year-round, it would be much more beneficial to its target buildings or residences. Another reason to use the system year-round would be to use the system in reverse and pump heated water throughout the system so that all snow and ice melts without the use of plows, sand and salt. This process is further discussed below.

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[24] Watts Radiant. (2008). Radiant Onyx.

VI.3.1 Use the System for Snow and Ice-Melting

There currently exist systems where heated fluid (with low freezing point) is pumped underground during winter months to heat up surfaces so that no ice or snow can ever cover the surface. Such a system is in place at the WPI campus, where the main staircase from the library parking lot (the one being used as the parking lot in this study) to the library is heated so that no snow or ice is ever left on the stairs. This requires little to no workers to shovel or clear off the stairs, saving the school the cost of labor. Companies such as Watts Radiant, mentioned above, specialize in the creation of these systems and more research should be put into whether or not a Smart Pavement could also be used to melt the snow and ice covering a parking lot.

If this were possible and economically feasible, then winter maintenance costs could be reduced significantly, adding to the benefits of installing a Smart Pavement beneath a given parking lot in areas where significant snowfall and frost is experienced. With slight changes in drainage structure, a parking lot could hypothetically never need to be plowed or shoveled at any time, as long as the Smart Pavement remained in a functioning state throughout the winter months and the melted snow and ice could be effectively removed from the surface without creating drainage issues.

One issue that arises with the current design and this recommendation is that it was determined through temperature testing that the area under parking spaces should be ignored when laying down the pipes of the Smart Pavement. This was due to the fact that the pavement's surface temperatures in these areas were low enough that there was the worry that running pipe under these areas would actually decrease the temperature of the water in the system. Some recorded temperatures underneath parked vehicles were as low as 14°C. If a design could be created that addressed this issue, or the heat transfer could be more closely studied using the aforementioned constant heat flux equations, then it may be possible to still run the pipes under the parking spaces, allowing for the entire parking lot surface to be "melt-able" in the winter months, at the same time allowing the system to output water in the warmer months.

Note that for using a fluid to melt ice in winter one need to use a fluid with lower

freezing point. One example would be a glycol based liquid, such as Dynalene

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VIII   Appendix A: Proposed Project Schedule

Schedule of Smart Pavements MQP
A Term
Finalize Proposal
Develop Database
Begin Stress/Strain Testing
B Term
Begin Modeling System
Conduct any experimentation
Begin Writing Report
Calculate necessary equations
Begin Flash Animation
C Term
Finish any necessary testing
Finish Writing Report
Finish Flash Animation
Presentation

Note: As of December 15, 2008

IX   Appendix B: MEPDG Files

See attached excel files for Chicago, Houston, Raleigh, and Portland.

X   Appendix C: Master List

See attached excel sheet Master List.

XI   Appendix D: Exit Temperature Calculations

See attached excel file.

XII   Appendix E: Temperature Determines Length

See attached excel file.