# ABSTRACT

Title of Document: DESIGN AND EVALUATION OF A RETROFITTABLE ELECTRIC SNOW MELTING SYSTEM FOR PAVEMENTS

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The objective of this research is to develop a novel electrically conductive heating system that can be retrofitted to existing asphalt pavements. This system is designed for permanent installation on the pavement surface, thus eliminating the expensive reconstruction required for embedded systems and the inconvenience of placing and then removing portable heating mats. The research approach combined theoretical analyses based on the physics of the problem, laboratory explorations of potential system components, and large scale testing to evaluate the constructability, functionality, and efficiency of the full system. The final system design consisted of a low-voltage grid of Nickel Chromium wire resistance heaters embedded in an asphalt sealcoat surface layer. Outdoor testing during an actual snowstorm conclusively demonstrated the effectiveness of the system for melting snow, even during continuing accumulations. Based on these evaluations, several practical designs suitable for production use are suggested. Installation and operating costs are also evaluated.

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By

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# Table of Contents

# List of Tables

# List of Figures

# Chapter 1: Introduction

## *Research Problem Statement and Objectives*

Team SnowMelt was formed to develop a practical and inexpensive method for preventing snow accumulation on paved surfaces such as residential driveways, sidewalks, and building entrances. The research concept is an electrically conductive heating system that can be retrofitted to asphalt surfaces. This concept as compared to existing pavement heating approaches has the advantages of eliminating the expensive reconstruction required for embedded systems that need to be installed below the paved surface and the inconvenience of placing and then removing portable heating mats before and after each snowfall.

Prior to developing prototypes for this system, the team developed a comprehensive understanding of the issues related to snowfall and the energy needed to effectively prevent accumulation. Snowfall during the winter months in the northern United States is a recurring nuisance for homeowners who must expend considerable time and energy clearing their driveways after each storm. Additionally, snowfalls kill hundreds of people each year in the United States through traffic accidents, overexertion, and exposure to the cold (Doesken, 1996). While there are no specific statistics dealing with deaths caused by shoveling snow, a study by the New England Journal of Medicine in 1993 concluded that people in poor physical condition increase their risk of a heart attack by over 100 times when shoveling snow and that even those who are in good physical condition may double their chances of having a heart attack due to overexertion (Roylance, 2009). A 1995 study in the Journal of the American Medical Association found that shoveling snow is equivalent to maximum effort on a treadmill for sedentary men in relation to their cardiovascular exertion (Roylance, 2009). By putting stress on the heart and raising blood pressure, shoveling snow can pose a significant health risk on the elderly, disabled, and others not physically fit. While the average person does not need to fear a heart attack each time they are forced to shovel snow, the potential to decrease the risk of heart attacks in America provides ample reason to develop a system that could eliminate a person's need to manually shovel a driveway.

The greater Baltimore/Washington DC area receives an average of 20 inches of snow per season (Dillinger, 2009), similar to areas such as New York and Philadelphia in terms of seasonal totals. Twenty inches of snow equates to an average of two to four snowstorms per year that affect a person's everyday routine. The proposed snow melting system aims to reduce the problems caused by snow accumulation on driveways and walkways while reducing the economic burden and physical demands associated with systems already on the market.

### *Research Approach*

The first step in designing the new snow removal system was to identify the societal problems that needed to be addressed. Out of this, a research objective was formulated that guided all future research and experimentation. Initial steps included a thorough literature review (Chapter 2) which focused on the various products that have already been developed to prevent snow accumulation and/or aid in its removal.

An examination of existing methods of snow removal provided insight into the perceived need for snow melting systems. The literature review also identified the benefits, limitations, successes, and failures of common snow melting methods such as salt spraying, geothermal underground heating, and conductive resistance heating. Ultimately, the benefits of all of these different systems need to be incorporated into any practical snow melting system for home use.

After examining all the potential sources and methods of snow removal, a theoretical analysis of the proposed approach was undertaken (Chapter 3). Using known scientific concepts such as Ohm's law, Joule's law, and thermodynamics, the energy and electrical requirements for melting snow were determined.

The next stage in the development process was to conduct laboratory evaluations of various materials, including asphalt sealant, conductive additives, and embedded wires (Chapter 3). After identifying the best materials for the system, three field evaluations were completed (Chapter 3). These field evaluations generated valuable data about the constructability, functionality, and efficiency of the system and provided insight into how to remedy the flaws in each prototype such as practicality, durability, and installation cost. Based on these field evaluations, several practical designs suitable for production use were suggested (Chapter 4). Economic analyses of these designs evaluated the installation and operating costs of running the snow melting system.

Ultimately, the project affirmatively answered the main research question: Can a conductive driveway sealant system suitable for retrofitting on existing pavements effectively, efficiently, and economically remove snow from residential driveways, sidewalks, and building entrances?  The final system developed in this study holistically integrates theory, laboratory experimentation, field evaluation, and engineering design to produce a marketable product.

# Chapter 2: Literature Review

The effects and inconvenience of snowfall on household residents are examined in this chapter to provide a context for the proposed driveway snow melting system. Environmental and economic issues of current de-icing and snow removal methods are also explored. The advantages and disadvantages of existing snow removal systems can be used to guide the design of the innovative snow removal system proposed in this thesis.

## *Financial Impacts of Snow Removal*

Northern states allocate significant budgets to snow removal. Although this scope is beyond that of a consumer product, it is still important to examine the financial impact of snow removal on a larger state level. For example, the Ohio Department of Transportation (ODOT) must plan for snowfall each winter ranging from 29 to 100 inches or more. With a fleet of 1,600 vehicles equipped with pavement sensors to relay road temperatures and conditions and 2,000 employed drivers, the snow removal crews spread granular salt, spray liquid calcium chloride ($CaCl_2$), and plow the road clear. ODOT spends an average of $24 million on winter operations and distributes over 500,000 tons of salt a year to sustain 48,000 miles of highways and 15,000 bridges (Snow Removal 2001).

These example statistics of the cost, equipment needs, and impact of snow removal on a community suggest the need for new innovative systems to remove snow more cost effectively and potentially with less environmental impact. The high cost of snow removal and the concomitant many hours of manpower may be reduced with an automated electrical system, at least for key facilities such as bridges, bus stops, and other localized areas. An electrical snow melting system could reduce annual state spending on snow removal.

This thesis describes the design of an innovative smaller scale snow removal system for consumer use that provides a more feasible alternative to the current salt and de-icing methods. For a homeowner, the cost of contracting residential snow removal has been estimated from $65-100/hr for snow plowing and more than $35/hr for repeated snow blowing with additional costs for salt application. An electrical snow melting system embedded in residential pavement areas and walkways can be conveniently operated to free the homeowner from performing strenuous manual shoveling or relying on a contractor’s availability. The installation, operating, and maintenance costs of such a system must rival the quoted costs of contracted snow removal services to be economical. An additional advantage of such a system is that the consumer can control the length of use and monitor the costs during operation instead of committing in advance to a pre-determined cost for contracted snow removal.

### *Hazards of Snow and Ice Accumulation*

The accumulation of snowfall and ice can pose physical hazards to home residents. Jason (1981) observed the neglect of snow removal of residential walkways in an urban Chicago neighborhood. During a 12-day observation period, this study noted that 50-60% of the 31 selected pathways remained untreated 35 hours after a snowstorm deposited more than 5 inches of accumulated snow. Letter notices produced only a 13% increase in shoveled pathways. With an accessible snow melting method, residents may be more inclined to clear walkways to improve safety and reduce the potential for injuries.

Björnstig et al (1997) found that in Umeå, Sweden, a suburban area of 118,544 inhabitants, an average of 3.5 injuries per 1000 inhabitants were observed over a one year period due to same-level surface slipping on ice and snow. Injuries were most frequent for women, comprising 61% of the 415 injuries. Elderly women 50-79 years of age were especially susceptible to falls, accounting for 34% of all injuries. For men, the age group of 20-29 years suffered the most injuries. The highest percentage of injuries occurred on pavements, streets, and roads, accounting for 47% of the total. An electrical snow melting system could reduce the occurrence of injuries and the consequent health care expenses.

Bentley and Haslam (1998) investigated 1734 fall cases for mail carriers of the Royal Mail system in Great Britain from April 1993 to March 1995 excluding reported unsafe acts. The estimated total employee population was 11,300. Of the total fall cases, approximately 50% of them occurred from November and February with foot slippage on ice and snow accounting for 60% of the cases. Additionally, 74% of all falls took place during the early morning delivery round, suggesting that the darkness and non-visible accumulation of frozen precipitation such as uncleared snow or black ice contributed to the accidents. Snow and ice along walkways pose definite potential physical hazards to and reduces the mobility of letter carriers and visitors. Other home services could be hindered by snow and ice as access into a residence becomes limited or blocked.

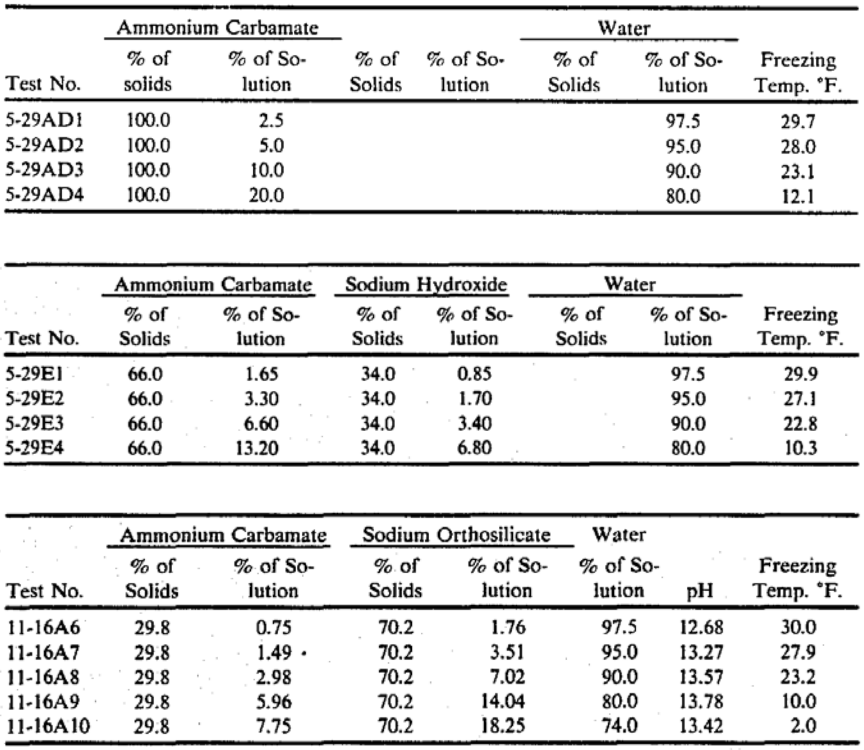
## *Current Snow Removal Methods*

### Deicing Chemicals

The main purpose of deicing chemicals and methods is to lower the freezing point of ice and snow and increase the freezing point depression ($T_f$) – the chemical process in which the freezing temperature of a liquid is lowered with the addition of a solute. Deicing chemicals do not use heat to physically or chemically melt frozen water. These chemicals are typically applied before a snowfall to prevent the freezing on roads by lowering the freezing point of water and thus easing manual removal of the slush. Since these deicing chemicals are mainly salts, their environmental implications must be considered as well.

Hansen (1987) noted that the popularity of salts, especially sodium chloride (NaCl), for deicing highways, bridge decks, and pavements is largely due to their low costs. Calcium chloride ($CaCl_2$) is considerably more expensive than NaCl but more effective as it depresses the freezing temperature ($T_f$) of water more than NaCl and in addition exothermically generates heat in solution. Both chloride salts pose a risk of chloride toxicity to plants and promote the corrosion of steel, particularly steel reinforcement in concrete. This corrosion will eventually compromise the structural integrity of bridge decks and structures. Hansen's study also examined the use of ammonium carbamate ($H_2NCO_2^- \cdot NH_4^+$), a hygroscopic fertilizer salt, as a deicing mixture. Ammonium carbamate is capable of lowering the $T_f$ of water further than $CaCl_2$ or NaCl. Several deicing compositions were used for removing snow or ice from concrete, reinforcing concrete and metal surfaces. As summarized in Table 1, changing the percentages of ammonium carbamate, water, sodium hydroxide, sodium orthosilicate, urea, and potassium hydroxide depressed freezing points to between 2 and 30°F.

**Table 1. Effectiveness of Lowering Freezing Point using Ammonium Carbamate Solutions at Various Concentrations (Hansen 1987).**



| | Ammonium Carbamate | | | | Water | | |
|---|---|---|---|---|---|---|---|
| Test No. | % of solids | % of Solution | % of Solids | % of Solution | % of Solids | % of Solution | Freezing Temp. °F. |
| 5-29AD1 | 100.0 | 2.5 | | | | 97.5 | 29.7 |
| 5-29AD2 | 100.0 | 5.0 | | | | 95.0 | 28.0 |
| 5-29AD3 | 100.0 | 10.0 | | | | 90.0 | 23.1 |
| 5-29AD4 | 100.0 | 20.0 | | | | 80.0 | 12.1 |

| | Ammonium Carbamate | | Sodium Hydroxide | | Water | | |
|---|---|---|---|---|---|---|---|
| Test No. | % of Solids | % of Solution | % of Solids | % of Solution | % of Solids | % of Solution | Freezing Temp. °F. |
| 5-29E1 | 66.0 | 1.65 | 34.0 | 0.85 | | 97.5 | 29.9 |
| 5-29E2 | 66.0 | 3.30 | 34.0 | 1.70 | | 95.0 | 27.1 |
| 5-29E3 | 66.0 | 6.60 | 34.0 | 3.40 | | 90.0 | 22.8 |
| 5-29E4 | 66.0 | 13.20 | 34.0 | 6.80 | | 80.0 | 10.3 |

| | Ammonium Carbamate | | Sodium Orthosilicate | | Water | | |
|---|---|---|---|---|---|---|---|
| Test No. | % of Solids | % of Solution | % of Solids | % of Solution | % of Solution | pH | Freezing Temp. °F. |
| 11-16A6 | 29.8 | 0.75 | 70.2 | 1.76 | 97.5 | 12.68 | 30.0 |
| 11-16A7 | 29.8 | 1.49 | 70.2 | 3.51 | 95.0 | 13.27 | 27.9 |
| 11-16A8 | 29.8 | 2.98 | 70.2 | 7.02 | 90.0 | 13.57 | 23.2 |
| 11-16A9 | 29.8 | 5.96 | 70.2 | 14.04 | 80.0 | 13.78 | 10.0 |
| 11-16A10 | 29.8 | 7.75 | 70.2 | 18.25 | 74.0 | 13.42 | 2.0 |

Ammonium carbamate was found to be effective at temperatures 14ºF colder than NaCl. The study also found that ammonium carbamate corroded steel considerably less than did NaCl and $CaCl_2$. The study concluded that an aqueous deicing solution of 40% ammonium carbamate by weight optimally lowered $T_f$ of water to 20°F and limited—but did not entirely eliminate—steel corrosion. Despite these advantages, ammonium carbamate is not currently produced industrially nor integrated into a commercial snow melting product due to its high cost (e.g., $159 for small 500g quantities from Sigma-Aldrich). Similar to other salt deicing solutions, ammonium carbamate salt still poses environmental impacts.

Alger (2005) details a three layer anti-icing coating to prevent the bonding of ice on to a surface for easier melting of snow and mechanical removal of accumulated ice. A 1/8-inch layer of solvent-free, moisture insensitive, two component epoxy was applied to the surface as a sealant to protect the underlying surface from contaminants and water. The epoxy met specifications of ASTM-C-881 Type III, Grade I, Classes B and C. A 1/4 to 3/4-inch thick aggregate layer of limestone or dolomite was sprayed on top of the wet epoxy layer. The aggregate size ranges from 1/8 to 1/4-inch. Then, an anti-icing layer of unspecified thickness was sprayed on top of the cured aggregate and epoxy layers. Anti-icing chemicals – such as sodium chloride (NaCl), potassium acetate (KA), calcium magnesium acetate (CMA), and propylene glycol with urea additive (PGU), all available in solution form – served to lower the freezing point of snow and ice. Surface frost growth simulation in a cold chamber at 30°F yielded no qualitatively observable ice formation on the pavement slab fitted with the anti-icing system whereas the control slab displayed ice on its surface.

Finally, the anti-icing layer can be reapplied if worn. Unfortunately, this method relies on the use of environmentally damaging salts.

Labadia and Buttle (1996) analyzed the extended effects of salt (NaCl) deicing on a major highway in Southern Ontario, Canada during the winter of 1994-1995. Along the 14km stretch of highway, the total amount of sprayed salt varied from 29 to 74 kg/m. Salt concentrations in the snow banks along the highway reached as high as 94,000 mg/L (volume in terms of water-equivalent amount of snow) – more than 10 times saltier than 0.9% weight by volume (9,000 mg/L) medical saline – late in the application season. This salt is transferred to the surrounding soil during snowmelt. Snow bank collections exhibited fluctuations in salt concentration between salting periods. Decreases of NaCl concentration in snow banks of up to 50% between sampling times were attributed to melt water runoff into the surrounding soil. Measurements of salt ion concentrations in the following summer of 1995 indicated that $Na^+$ and $Cl^-$ concentrations within the upper 2m of soil were higher than 500mg/L and 1000mg/L, respectively. Approximately 75% of the net flux of NaCl into the upper soil layer between 0-2.8m was retained. These high salt concentrations in the soil could limit the amount of water available to plants, deteriorate soil aggregates, and decrease the permeability of the soil to air. These effects could inhibit the growth of plants and have prolonged damaging effects on the surrounding soil.

### Conductive Self-Heating Materials

Conductive polymers are electrically conductive organic chemical compounds with valence electrons that can be delocalized. Pratt (1996) described how conductive polymers store and transport charges at the atomic level and how other properties such as stability and processibility might affect their applications. Conductive polymers store charges by losing an electron from oxidation or by the localization of the charge over a small section of the polymer chain. The conduction mechanisms used by these polymers is via movement of electrons between localized sites at different states as well as by thermally activated hopping or tunneling movement between highly conducting domains. Conductive polymers have two types of stability: extrinsic and intrinsic. Extrinsic stability refers to a polymer being able to withstand environmental degradation from oxygen, water and peroxides. Intrinsic instability refers to a polymer's tendency to degrade over time after repeated chemical and thermal reactions. There are many potential uses for these polymers because of their conductivity and electroactivity. However, practical applications have been limited to date because polymer stability and processing techniques need to be improved before these materials can be used reliably in products. In addition, current costs are too high for profitability. Conductive polymers may very well be the cutting edge for use in future products. However, at present they are not economically viable for use in large scale heating applications.

Chung (2004) experimented with several types of materials and composites to determine the optimal design for self-heating pavement materials. The experiments consisted of two categories of materials: self-heating cement-matrix composites and self-heating continuous fiber polymer-matrix composites. The materials tested and their performance data are summarized in Table 2.

**Table 2. Effectiveness of self-heating from a room temperature of 19°C (Chung 2004).**

|  | Material | Maximum temperature (°C) | Time to reach half of the maximum temperature rise | Power (W) | Volume resistivity (Ω cm) | Reference |
|---|---|---|---|---|---|---|
| 1 | Steel fiber (0.7 vol%) cement | 60 | 6 min | 5.6 | 0.85 | [44] |
| 2 | Carbon fiber (1.0 vol%) cement | 56 | 4 min | 1.8 | 100 | [44] |
| 3 | Graphite particle (37 vol%) cement | 24 | 4 min | 0.27 | 410 | [44] |
| 4 | Carbon fiber (uncoated) mat | 134 | 2 min | 6.5 | 0.11 | [45] |
| 5 | Ni/Cu/Ni-coated carbon fiber mat | 79 | 14 s | 3.0 | 0.07 | [45] |
| 6 | Carbon fiber epoxy–matrix interlaminar interface | 89 | 16 s | 0.59 | [b] | [46] |
| 7 | Flexible graphite[a] | 980 | 4 s | 94 | $7.5 \times 10^{-4}$ | [47] |

[a] Not a structural material.

[b] The relevant quantity is the contact resistivity rather than the volume resistivity.

In the first category, steel fiber, carbon fiber and graphite particles were mixed into Portland cement. A 0.7% by volume mix of 8 µm-diameter steel fibers was found to have exceptionally low electrical resistivity (0.85 Ω-cm) and thus high effectiveness for heating. At a direct current electrical power input of 5.6 watts (0.79 amps at 7.1 volts), the material increased in temperature from 19°C to a maximum of 60°C after 6 minutes and achieved 100% energy conversion efficiency after 50 minutes with a steady-state heat output of 750W/m. The steel fibers did not require special equipment or aggregate to mix with the cement. Similarly, a carbon fiber cement mixture (1.0% by volume mix of carbon fibers) had a resistivity of 104 Ω-cm and reached a maximum temperature of 56°C at a power input of 1.8 W (0.065A at 28V). The system reached half of its maximum temperature in 4.3 minutes, which was slower than for the steel fiber cement mixture. The carbon fibers were deemed less desirable than steel fibers because of the higher operating voltage required, as compared to the 7V necessary for the steel fiber cement. The graphite particle (37% by volume) cement paste had even worse performance as indicated in Table 2. The second category of materials consisted of continuous fiber polymer matrix composites in two configurations: low resistivity interlayers (mats) and interlaminar interfaces (Table 2). One example is a porous mat made from short carbon fibers and an organic binder. A mat with a resistivity of 0.11 Ω-cm provided heating up to 134°C at a power of 6.5 W and required only 1.8 minutes to reach half the maximum temperature. Another example is a mat made from Ni/Cu/Ni tri-layer coated carbon fibers with a resistivity of 0.07 Ω-cm, which provided heating up to 79°C and required only 14s to reach half the maximum temperature. Finally, an interlaminar interface was created between two crossply laminae of a continuous carbon fiber epoxy matrix composite. The interface area was 5mm x 5mm and had a resistance of 0.067 Ω. At a DC power input of 0.59W (3.0A, 0.20V), it reached a maximum temperature of 89°C and took 16s to reach half the maximum temperature. A 100% efficiency was reached after 55s at a steady state heat power output of $4x10^4$ W/m2.

These studies provided guidance and test data for the types of materials that could be used in designing an electric snow melting system for pavements. In addition, it suggested which components could be best for the two types of self heating materials. The disadvantages are that some of these materials are very costly to purchase and require time and skill to create, especially for the mats and interfaces. Incorporating these materials into a homeowner-applied product would be difficult.

### Geothermal Heating

Ichiyama and Magome (2007) developed a system utilizing underground galvanized steel pipes to pass a geothermally heated fluid, such as water or antifreeze solutions, through the pavement to increase the surface temperature and melt snow. A test panel was constructed from a single 50m carbon-steel pipe conforming to JIS G3452 with an outer diameter of 21.7mm and wall thickness of 2.8mm. The carbon-steel pipe was bent into a serpentine designed such that overall dimensions of the prototype panel were 2.5m x 2.5m with 200mm spacing to facilitate heat transfer and a uniform surface temperature distribution.

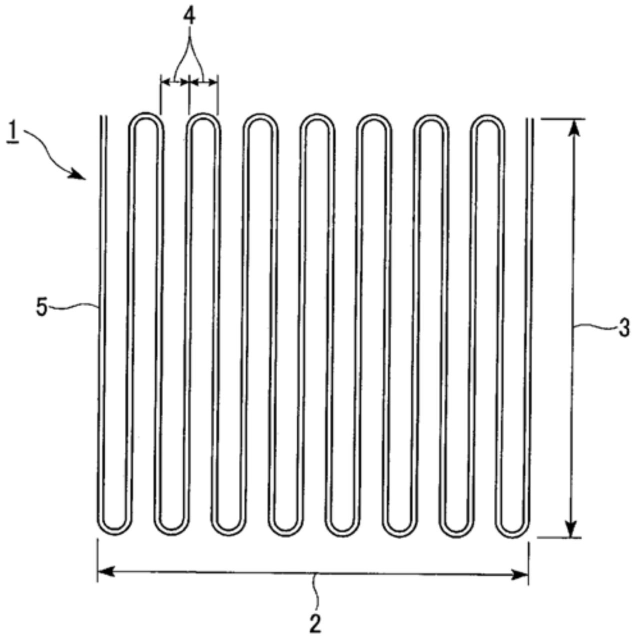


**Figure 1. Layout of Serpentine Geothermal Pipes (Ichiyama and Magome 2007).**

The use of a single long pipe was considered the best option because it reduced the need for welded joints and the consequent corrosion potential and increased construction cost. A novel aspect of this underground heating pipe system was the incorporation of hot-dip galvanization. The corrosion resistant galvanized layer was composed of 2 to 19% aluminum, 1 to 10% magnesium, and 0.01 to 2% silicon (with the combined maximum content of aluminum and magnesium as 20%). This product is sold commercially as SuperDyma™ by the Nippon Steel Corporation. Galvanizing protects the pipes from corrosion from salt that potentially could have seeped through the overlying asphalt pavement. It also permitted use of corrosive antifreeze agents. This study demonstrated that a geothermal design can melt snow while minimizing possible harmful environmental and human health hazards. The glaring limitation of this heating system is that it must be installed underground, requiring the removal and reconstruction of the existing pavement as well as drilling of the geothermal wells. This installation process may be too costly and inconvenient for widespread implementation, especially for existing pavements. However, an underground geothermal heating system could be a potential marketing angle for contractors building new homes and businesses.

Dutch engineer Arian de Bondt (*The Economist* 2007) designed an underground water pipe heating system for asphalt pavements. Designed ten years ago, this system utilizes ground water from aquifers below the surface. The water from these aquifers is pumped to the surface on warm days, where the water picks up the heat from the sun on the asphalt. In the winter this stored warm water is pumped back up to the surface in order to heat it. While originally designed for warming the roofs of buildings, it is possible to adapt something similar to warm a road surface in order to melt snow in the winter.

Lund (2000) noted that the installation costs for underground residential geothermal systems are approximately ~\$20/ft$^2$ plus the cost of the pumping system and wells. Highway bridge deck systems can cost \$100-150/ft$^2$ including heat pipes and heating system. These estimates suggest that a residential geothermal snow melting system may be too costly to install and operate.

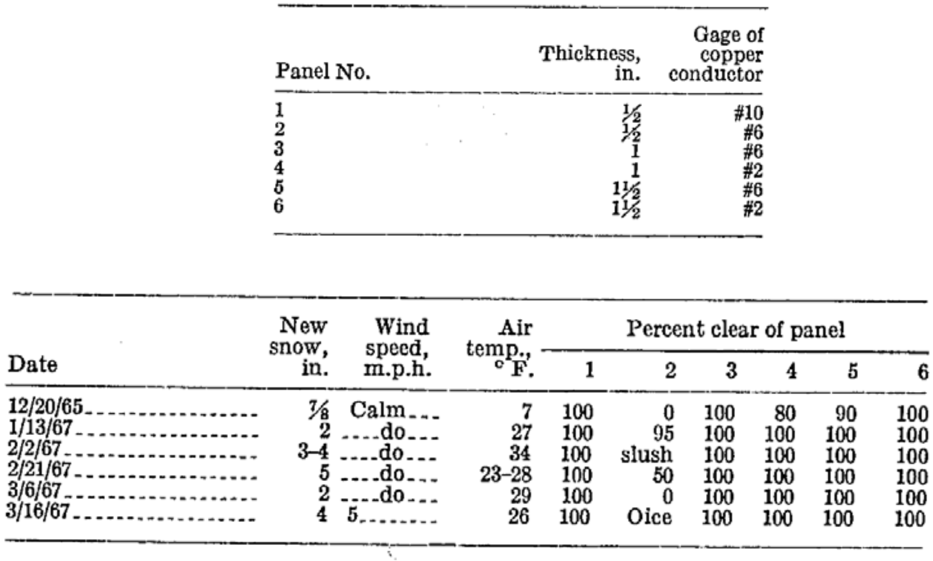
### Electrical Heating

Sugarawa et al (1998) designed an electrical pavement snow melting system outfitted with a monitoring device receiving weather probability data compiled by the Japan Meteorological Association. Analyzing snowfall probability, road surface temperature, atmospheric temperature, and control temperature, this monitoring system allowed for the adjustment of surface preheating temperature and the energy output sent to the embedded heating wires. The energy supplied to the four-parameter monitoring system ranged from 168.7 kWh/m$^2$ to 175.2 kWh/m$^2$ (18.64 kWh/ft$^2$ to 19.47 kWh/ft$^2$). Without the monitoring system, the energy output ranged from 222.2 kWh/m$^2$ to 455.7 kWh/m$^2$ (24.69 kWh/ft$^2$ to 50.63 kWh/ft$^2$).

Petrenko and Sullian (2003) describe an electromagnetic ice melting system in which alternating current passing through an electrical conductor generates an electromagnetic field. The energy from the electromagnetic field is absorbed by a ferroelectric, lossy dielectric, semiconductor, or ferromagnetic coating that transfers the heat to the surface. The dielectric or magnetic loss is temperature dependent, which can control the absorption and transfer of electromagnetic energy only at below freezing temperature. This system was designed to heat power lines that, on average, carry 10kV at 60Hz to generate a sufficient alternating electromagnetic energy for absorption. The extremely high suggested voltage is hazardous for consumer use. However, the design of heat conductance through a surface coating is similar to SnowMelt's goal of generating resistance heating through a driveway sealant.

Minsk (1971) incorporated graphite particles to make an electrically conductive asphalt concrete. A sufficient quantity of graphite particles was incorporated to produce a resistivity of 1 to 5 Ω-inch. The specific asphaltic concrete mixture tested in the study consisted of 13.8% of 9/16-inch crushed stone, 27.5% of 3.8-inch crush stone, 32.1% of sand, 8.3% of asphaltic cement, and 18.3% of high purity graphite particles (all percentages by total weight of mix). To ensure an even distribution of the materials, the mixture was maintained at a temperature of 350ºF during the mixing process. Copper cables serving as busses were spaced at regular intervals and connected to a suitable power source and then covered by a thin surface layer of the conductive asphalt mixture. Power dissipation was targeted within the range of 10 to 40 W/ft$^2$. In most cases, a spacing of 5 feet between electrodes was employed, which produced a gradient of 6 volts per foot with a total system voltage of 30V. Various gages of copper wires and thickness of conductive concrete were tested on 6 panels.

**Table 3. Performance of Conductive Asphaltic Panels (Minsk 1971)**



| Panel No. | Thickness, in. | Gage of copper conductor |
|---|---|---|
| 1 | ½ | #10 |
| 2 | ½ | #6 |
| 3 | 1 | #6 |
| 4 | 1 | #2 |
| 5 | 1½ | #6 |
| 6 | 1½ | #2 |

| Date | New snow, in. | Wind speed, m.p.h. | Air temp., °F. | Percent clear of panel | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | 4 | 5 | 6 |
| 12/20/65 | ⅞ | Calm | 7 | 100 | 0 | 100 | 80 | 90 | 100 |
| 1/13/67 | 2 | do | 27 | 100 | 95 | 100 | 100 | 100 | 100 |
| 2/2/67 | 3-4 | do | 34 | 100 | slush | 100 | 100 | 100 | 100 |
| 2/21/67 | 5 | do | 23-28 | 100 | 50 | 100 | 100 | 100 | 100 |
| 3/6/67 | 2 | do | 29 | 100 | 0 | 100 | 100 | 100 | 100 |
| 3/16/67 | 4 | 5 | 26 | 100 | Oice | 100 | 100 | 100 | 100 |

Panel 2 was noted to have a lower power dissipation of 3 to 7W instead of the desired 10 to 40W. The study however did not determine the duration of operation for the system to clear each panel.

An advantage of Minsk's system is that the conductive pavement material can be easily applied as a thin overlay to existing pavement materials, avoiding the need for major reconstruction. Minsk suggests that the conductive layer should not exceed 2 inches in thickness because of cost considerations and should not be less than ½ of an inch for durability. Additionally, Minsk recommends that areas subject to heavy wear be covered by a nonconductive layer of ½ to 1 ½ inches in thickness. The major contribution of this study was the development of an effective method of making asphalt conductive and a way to pass a current through the conductive layer. However, very high concentrations of graphite are required, and this material is expensive (e.g., $187.59 for 12kg from Sigma-Aldrich). This system would therefore not be cost effective.

At O'Hare International Airport, Derwin *et al.* (2003) from Superior Graphite Company, with testing and evaluation collaboration from the Federal Aviation Administration and the Flood Testing Laboratories, developed the Snowfree® electrically conductive asphalt pavement system to melt snow from runways. The system was implemented and evaluated for 3.5 years. This pavement system was composed of three layers: the base, the conductive asphalt, and the cover. The base can either be concrete or asphalt. The conductive layer involves laying down copper cables at 16ft spacing over each 70 x 97ft heating segment. A 2-inch conductive asphalt layer composed of ~25% thermally purified graphite was applied on top of the copper cables. The thickness of the cables was not mentioned in the publication. A 2-inch layer of asphalt covered the top and sides of the conductive layer. Alternating live and ground electric wires were connected to the copper cables. The target operating efficiency was 12.8 watts/°F/ft$^2$ (dependent on the air temperature) assuming an initial 25°F air and surface temperature and 10mph winds. Operating at 120V and 830A through each cable, the system generated a power density of 45 watts/ft$^2$. The start-up heating time required to increase the surface temperature from 25°F to approximately 34°F was ~2.5hrs. The study estimated an operational heating cost of ~$2,400/hr for a 10,000ft runway and an installation cost of ~$15/ft$^2$. Additionally, the durability of the asphalt mix met the FAA P401 regulation for airport surfaces with a custom blend of aggregates and graphite. Through 200,000 departing aircraft and temperatures ranging from -10°F to 100°F for about 4 years, no significant cracking was observed. With a power of 45 watts/ft$^2$, the system could be affordable for consumer use. Applicable to SnowMelt's aim, assuming a 40-foot driveway with the width of 70ft, the heating cost would be approximately \$9.60/hr according to the estimated costs provided. With lighter traffic on a home driveway, this system design could have greater durability.

Walker (2000) developed a three-layer snow and ice melting blanket, as well as devices for measuring temperature and snowfall weight. As shown in Figure 1, the top and bottom layers of the blanket consist of a tarpaulin material that is both flexible and waterproof. Between the two tarpaulins is a layer of conductive metal. Temperature and weight sensors were also built into the system. Another innovative aspect of this system was a curved support structure positioned below the tarpaulins to allow snow and melted ice to flow off of the mat.

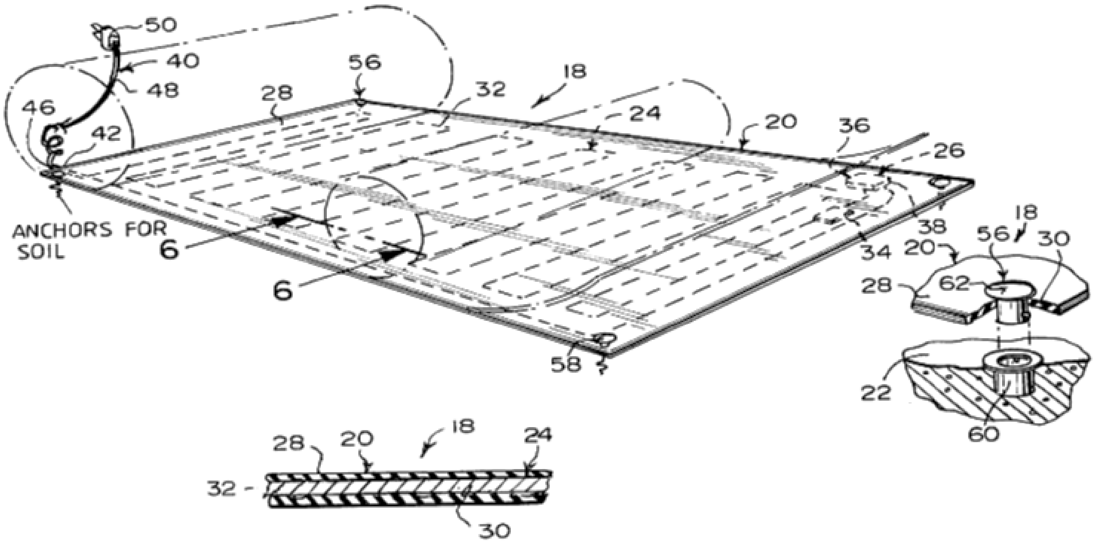


**Figure 2**. **Layout of 3-Layer Serpentine Heating Mat (Walker 2000).**

When the sensors determined that the temperature was below freezing and enough weight has accumulated, current was switched on to the conductive layer. Once the snow and ice have melted, the weight drops below a threshold and the current is turned off. This snow and ice melting blanket can be placed on a flat roof, autonomously operated, and easily rolled and stored when not needed. This blanket demonstrated a practical way of making a snow melting system operate without manual monitoring and control, thus saving electrical costs from unnecessary overuse. The limitation of this heating system is that it is not permanent. Additionally, this device is designed for roofs and does not have the durability required for a pavement system subjected to traffic.

Similar to Walker, Abuksam (2001) designed a patented snow-melting mat consisting of a mesh of conductive wires and heating elements. The mat was formed from durable and resilient electrically insulating hard molded thermoplastics and hard rubber that supported vehicular weights while resisting environmental conditions such as moisture, rain, snow, salt, and solar UV radiation. The 1 to 2cm thick mat contained a pair of 220V conductors running along the edges. Parallel heating wires connected to the edge conductors spanned the width of the mat. The overall dimensions of the mat can be tailored to the size of the pavement. Multiple mats can be interconnected for larger areas. Operation is controlled by a temperature sensor embedded into the mat. A precipitation detector deactivates the system when a sufficient amount of melt water is sensed on the surface. The product design demonstrated the use of a mesh system of conductive metal wires to generate heat and evenly distribute electrical current. The ability to retrofit the mat to existing pathways and pavements is also an advantage that would appeal to existing home owners.

*Design Studies*

Chapman and Katunich (1956) formulated a generalized model equation for the amount of sensible heat required to melt snow on a surface:

$$q_o = q_s + q_m + A_r (q_e + q_h)$$

in which:

$q_s$ = sensible heat transferred to the snow (Btu/h·ft$^2$),
$q_m$ = heat of fusion of water (Btu/h•ft$^2$),
$A_r$ = ratio of snow-free area to total area,
$q_e$ = heat of evaporation (Btu/h•ft$^2$),
$q_h$ = heat transfer by convection and radiation (Btu/h•ft$^2$).

From the general equation shown above, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE, 1995) estimated the energy requirements for melting snow on pavements in selected cities. These estimates are summarized in Table 4 below.

**Table 4**. **Estimated energy requirements for melting snow on pavements (Chapman and Katunich, 1956)**

| | Design Output (W/m$^2$) | | |
|---|---|---|---|
| **City** | **Class I System** | **Class II System** | **Class III System** |
| New York City, NY | 381.2 | 938.9 | 1077.5 |
| Chicago, IL | 280.4 | 519.8 | 1102.7 |
| Reno, NV | 308.8 | 485.2 | 488.3 |
| Portland, OR | 270.9 | 305.6 | 349.7 |

As described by Chapman (1957), Class I System was categorized as residential walks, driveways, paths. These values are consistent with the power requirements noted in Minsk (1971) of ~40W/ft$^2$ and Derwin et al (2003) of ~45W/ft$^2$ and can serve as a guide for determining the required power output when designing a residential snow melting system.

Liu et al (2007) noted that previous theoretical models for sub-surface heating systems focused on steady state snow accumulation. They suggest the need to develop a transient model to account for the variability of weather conditions, snowfall rate, discrete distribution of heat to the surface, and the insulation effects of the unmelted snow. This transient model needs to account for not only the current surface conditions but also the prior conditions and the heat flux through the pavement system. During the melting process, there are three distinct layers – water, slush, and dry snow – that have different thermal properties. Thus, any electrical snow melting system will require an adaptable dynamic control system for optimal efficiency.

### *Safety Concerns*

Electrical heating of pavement systems introduces the potential for electric shock to pedestrians and vehicle occupants. This potential will be a function primarily of the system voltage and current capacity.

Bikson (2004) provides an overview of the effects of transdermal current exposure on the human anatomy. The review sought to determine the safe human threshold voltage level, or the voltage at which an electrical current applied to the human skin will result in damage. Conditions influencing this threshold include the presence of moisture and the duration of contact with the live current. The three primary mechanisms of injury are the pain/let-go response, respiratory paralysis, and current induced ventricular fibrillation. Since respiratory paralysis and ventricular fibrillation are both fatal if not swiftly treated, the voltage levels causing these injuries were considered fatal. Since the pain/let-go injury causes observable physical discomfort, voltage levels causing this injury were considered unsafe. Dry skin has a normal resistance ranging from 1,000Ω to 100,000Ω , sufficiently high to poorly conduct enough electricity to cause physical damage. Thus, as a worst case scenario, at an estimated human body resistance of ~550Ω, a sustained voltage of 16.5V will generate a current of 30mA, sufficient to cause respiratory paralysis after 1 minute. A 27.5 sustained voltage will generate a current exceeding 40mA, sufficient to induce cardiac arrest at within one minute; at 55V and 100mA current, cardiac arrest occurs in 1 second. The lowest voltage actually observed for adult transdermal electrocution is 25V. Therefore, these worst-case scenarios would require a large wet-conductive contact surface with minimal skin resistance.

Bikson cites that the International Electrotechnical Commission (IEC) report 60634-4-41 (2001) advises that protection is unnecessary for unearthed exposed circuits if they do not exceed 25V RMS alternating current ($35V_{PEAK}$) or 60V direct current. The Occupational Safety and Health Administration (OSHA) (2004) specifies that exposed live parts of electrical equipment operating at 50V or higher require guarded enclosures from accidental human contact. Additionally, Greenwald and Greenwald (1991) state that voltages between 30 and 50V at 60Hz can be safe. Electrocutions from electric arc welders were reported at 80V when direct unobstructed skin contact was made with the electrodes. However, clothes can obstruct the current path to lessen the occurrence of electrocutions.

A snow melting system must not pose electrical hazards to pedestrian traffic on the surface. As noted by the safety guidelines, an electric snow melting system can operate safely up to a conservative $50V_{PEAK}$ alternating current without any precautions to limit accidental exposure to the user.

## *Conclusion*

Snowfall and ice accumulation pose physical and occupational hazards ranging from from slipping and falls (e.g., for elderly women and mail deliverers) to shoveling-induced heart attacks. On a large scale, the snow removal requires considerable budget allotments by state governments and significant labor. For homeowners, relying on private contractors can be expensive and require long-term contractual commitments. An easily accessible consumer snow melting system could alleviate many of the physical injuries and mobility restrictions from the accumulation of snow and ice. The convenience of an easily-operated electric snow melting system would increase the incentive for the consumer to maintain safe and clean access to their homes.

The current popular method of deicing salts exacerbates the corrosion of concrete pavement and its steel reinforcements and causes environmental damage to soils and vegetation adjacent to the pavement. Deicing salts are primarily a preemptive measure to lower the freezing point of water and are ineffective in melting and removing snowfall after it accumulates. New methods of melting snow involve the use of heat conduction through geothermal and electrical resistance heating. However, pavements containing conductive materials are too costly to be marketed for consumer use. Underground geothermal heating is not retrofittable on existing pavement surfaces, another disadvantage.

Patented retrofittable electric heating mats can reduce installation costs and are suitable for home use. Most of these heating systems operate at safe low voltages less than 50V and amperage within safe electrical parameters outlined by OSHA and IEC regulations. However, electric heating mats must be placed and removed for each snowfall event, a major drawback to practical use.

Expanding on these prior developments, SnowMelt aims to design and evaluate a sealant electric heating system that can be retrofitted on existing asphalt driveway pavements.

# Chapter 3: Methodology

This chapter describes the laboratory and field testing performed by the team to evaluate potential snow melting system designs under various conditions and on various scales. Theoretical calculations used to estimate power requirements for the system will be presented first, followed by descriptions of the preliminary laboratory testing, used to identify suitable materials and techniques for a large-scale evaluation. The subsequent prototyping in the laboratory based on these results will then be detailed, including the laboratory scale system performance data. Next, the first field implementation of a prototype system will then be detailed, including discussion of potential improvements which were suggested by test results. This will be followed by the description and analysis of the second set of field tests, serving as a final proof of concept evaluation prior to suggestions regarding potential implementation.

## *Theoretical Calculations*

This section documents the theoretical estimation of the power required to melt snow. These estimates are based on standard physics theory, including some simplifying assumptions, and on literature-derived values for key constants and material properties. The overall objective of this effort is to assess system requirements under real-world conditions.

### Assumptions

Prior to calculating the power requirements of the system, assumptions must be made to simplify the calculations. First, the exact density of snow varies. The snow water equivalent (SWE) is the amount of water contained in a snowpack. Typical SWE of snow is between 10 and 20% (NRCS, 2010).

Second, only the latent heat of water—i.e., the energy required to change a given mass of water from the solid to liquid phase--will be considered. The latent heat of water is 334 J/g. The heat required to raise the temperature of ice to the melting point is ignored in the calculations because it is insignificant compared to the latent heat.

Third, the system will not be 100% efficient. Not all the heat produced is used to melt snow. Heat loss occurs through conduction to the ground and through convection and radiation to the surrounding air. Transient heat loss can also occur as the system heats up due to the thermal inertia of the ground. Up to 50 percent of heat generated can be lost through the ground (Williams, 1974). Losses to the surrounding air can be reduced if the system is allowed to be covered with snow before being turned on. Based on engineering judgment, a 50% thermal efficiency factor is assumed for the purposes of these calculations. The actual efficiency factor will be evaluated during the research as part of the large scale testing described later in Chapter 3.

Fourth, the maximum safe voltage to which humans can safely be exposed is 50V. This value was taken from Occupational Safety and Health Administration (OSHA) regulations. Therefore, the system design was capped at 20 volts to provide an additional margin of safety.

Equations

Using the assumptions stated above, one can calculate the heat necessary to melt 2.54 cm of snow in one hour on a 1 x 1 meter square. This can be done by applying three basic physics equations:

Joule's Law: $Q = I^2Rt = \frac{V^2}{R}t$ (1)

Ohm's law: $V = IR$ (2)

Power: $P = VI$ (3)

in which
Q = energy (joules, J)
P = power (watts, W)
I = current (amperes, A)
R = resistance (ohms, Ω)
V = voltage (volts, V)
t = time (sec)

Using the assumptions of 10% SWE, 50% efficiency, and the latent heat of water, the energy required to melt 2.54 cm of snow over one square meter area is $Q = 1.70 \times 10^6$ J. This value of Q is substituted in Eq. (1) giving a target resistance R = 0.85 Ω across the 1 x 1 meter square area at the assumed system voltage of 20V and melting time of 3600 seconds (1 hour). Substituting this resistance into Eq. (2) and the definition of Eq. (3) yields P = 471 W. Thus, the target power density to melt 2.54 cm of snow over one square meter area is 471 W/m$^2$.

It is important to note that the target resistance changes with area, as shown in Table 5. An increase in area increases the total power required, which at a fixed voltage can be achieved only by reducing the resistance of the system. For example, a two square meter area will have a target resistance of 0.42 **Ω**. As a result, the target resistance for a residential system will be less than one ohm.

**Table 5. Calculated resistance values based on area of surface.**

| Area ($m^2$) | Resistance (Ω) |
|---|---|
| 0.5 | 1.7 |
| 1.0 | 0.85 |
| 1.5 | 0.57 |
| 2.0 | 0.42 |
| 2.5 | 0.34 |
| 3.0 | 0.28 |
| 3.5 | 0.24 |

The calculated power density of 471 $W/m^2$ is higher than the design guidelines in the literature for Class I residential systems[1] summarized previously in Table 4 (Chapman and Katunich, 1956). However, the calculations are for the lowest efficiency expected from the literature review. Overall, the many simplifying assumptions and approximations in the calculations are reasonable.

### *Laboratory Evaluation*

This section outlines the preliminary testing done in the laboratory to identify and evaluate suitable materials for the snow melting system. The laboratory testing was organized into two phases. The first phase evaluated conductive materials dispersed

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[1] The purpose of our system is for residential driveways, making it a Class I system. See Literature Review for further information.

through the sealant to render it electrically conductive. The second phase evaluated the use of conductive wires covered by a layer of sealant.

### Conductive Sealant Testing

Initial testing was performed to identify the conductive properties of coal-tar based asphalt sealant. These tests used a typical driveway sealant commonly found in hardware stores (Blackjack Drive-Seal 200, see specification sheet in Appendix B). A 500 mL sample of sealant was placed into a 15 x 15 x 9 cm non-conductive plastic container. The resistance was measured by immersing the probes of a digital multimeter (Fluke 179 True RMS Multimeter) at approximately 13 cm spacing. The resistance of this well mixed sample of sealant was 280-350 kΩ, with a median of 310kΩ. This resistance is much too high to pass sufficient current and thus is not feasible for generating heat.

The first test was to determine if cheaper fillers could be used to increase the conductivity of the sealant. As mentioned before, the conductive polymers described by Chung (2004) were too expensive. Samples of various materials were added to the sealant in various concentrations (Table 6). The first substance tested was graphite powder. 7.5 g of the powder was added to a 77.7 g sample of sealant in a 15 x 15 x 9 cm non-conductive container. This sample had a measured resistance fluctuating between 180 and 230 kΩ, with a median of 205kΩ. This is considerably higher than the target 1 Ω for this geometric configuration.

The next substance tested was copper powder (Fluka). A sample of 7.5 g of powder was added to 75.3 g of sealant in a similar non-conductive container. This yielded a lower resistance of 100 to 150 kΩ, with a median of 125kΩ. This resistance is still too high to permit any meaningful current flow. A similar approach was attempted using scrap aluminum shavings. These did not decrease the overall resistance of the sealant, yielding similar results to the copper powder.

Increased concentrations were ineffective in substantially decreasing resistance. The high resistance encountered in these tests indicated that conductive powders were unable to form a continuous flow path for the electrical current. An alternate method of changing the conductive properties of the sealant was required. The next series of tests therefore used a conductive mesh immersed in sealant such that a continuous circuit was formed.

A sheet of carbon fiber mesh with a mass of 0.5 g was placed at the bottom of a 15 x 15 x 9 cm non-conductive container. Then 114.5 g sample of sealant was poured over the sheet, enough to completely immerse the carbon fiber. Resistance measured by immersing the Fluke meter probes in the sealant sample, though not in contact with the carbon fiber, was 25-38 kΩ, with a median of 31.5kΩ. When the probes were placed in direct contact with the mesh, measured resistance fell sharply to 1.5-2.5 Ω, with a median of 2 Ω.

The steel wool sample produced similar results. Placed in a similar non-conductive container, a sample of common household steel wool was covered with 207.2g of sealant. When the probes were immersed only in the sealant and not in contact with the steel wool, resistance was 30-55 kΩ, with a median of 42.5kΩ. The resistance fell to 1.5Ω to 2.5Ω when the probes were placed in direct contact with the steel wool.

**Table 6. The resistance values for various materials in the driveway sealant. Additional readings were taken with the probes in direct contact for non-powder additives.**

| Substance | Amount Added (g) | Sealant Added (g) | Resistance (Ω)[2] |
|---|---|---|---|
| West System 423 Graphite Powder (96-100% Graphite 0-4% Silica) | 7.5 | 77.7 | 180-230 kΩ |
| Fluka Copper Powder (purum p.a., ≥99.0%, powder) | 7.5 | 75.3 | 100-150 kΩ |
| Aluminum Shavings (95% Al 5% other metals) | 3.0 | 76.5 | 100-150 kΩ (sealant)<br>2-4 Ω (shavings) |
| Fibre Glast Carbon Fiber Mesh (6K 5HS Weave 10.1 oz) | 0.5 | 114.5 | 25-38 kΩ (sealant)<br>1.5-2.5 Ω (mesh) |
| Steel Wool | 3.0 | 207.2 | 30-55 kΩ (sealant)<br>1.5-2.5 Ω (wool) |

The resistance of all materials was much higher than the estimated target resistance for generating sufficient heat. However, the tests still provided valuable data. The dramatically lower resistance of both steel wool and carbon fiber mesh immersed in sealant indicated that layering sealant over a conductive layer was a viable experimental approach. This led to a new design concept utilizing a continuous wire circuit encapsulated in sealant.

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[2] Probes were spaced 13 cm apart.

Small Scale Asphalt Puck Testing

Initial testing in this phase focused on determining the optimal type of wire for use as a resistive heating element under the seal coat. A number of different types of wire were selected based on their known conductive properties. These properties were confirmed via ohmmeter measurements. An infrared thermometer (Fluke-61 Noncontact Thermometer) was used to determine the temperature increase generated by current flow through the wire. Each 33 cm length of wire was connected to a CW-80 Lionel train transformer (Figure 3). This variable-voltage transformer was internally limited to a maximum current flow of 5 amps.

**Figure 3. The Lionel CW-80 Train Transformer**

Table 7 summarizes the various types and gauges of wire that were tested to determine which, if any, fell within the target resistance range, The Fluke multimeter was used to measure all resistances and voltage drops.

**Table 7. The resistance of a meter long wire of various materials.**

| Wire | Resistance (Ω/m) |
|---|---|
| 22 Gauge Steel Galvanized | 0.98 |
| Ook Brand 22 Gauge (50 lb Capacity) Durasteel Stainless Steel Picture Wire | 3.28 |
| Ook Brand 100 lb Capacity Durasteel Stainless Steel Picture Wire | 1.31 |
| Omega Brand 18 Gauge Nickel Chromium (80%Ni 20%Cr) | 1.31 |
| Omega Brand 22 Gauge Nickel Chromium (80%Ni 20%Cr) | 3.94 |

All of the tested wire types had much lower resistances than the previous tests. For larger test areas that would require a lower resistance (less than 1 ohm), the wires could be laid in a parallel circuit to achieve a lower total resistance. The Nickel Chromium (NiChrome) wire was selected based on its usage as a resistance heating element in common devices such as toasters, furnaces, and space heaters. To confirm that it would work in this application, a small-scale model was created for testing in the laboratory. Approximately one meter of 18 Gauge NiChrome wire was placed in a serpentine pattern on the flat surface of a 150 mm diameter asphalt cylinder (Figure 4). The wires were placed such that they were separated by a distance no greater than 50 mm at any given point.

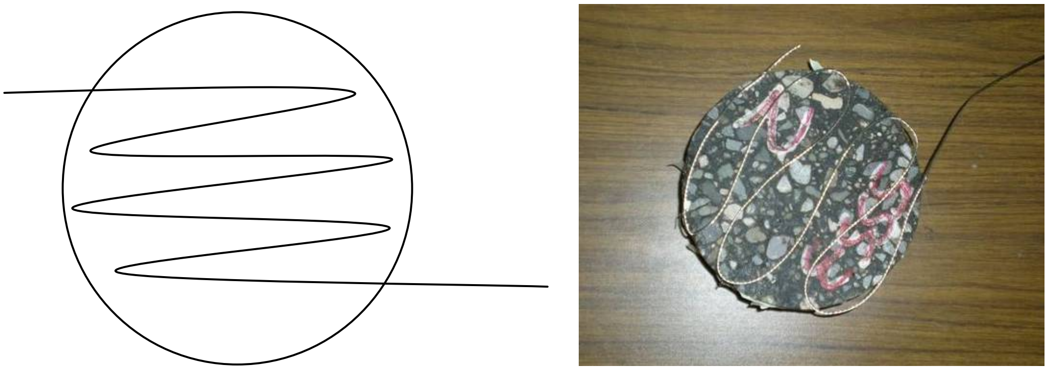

**Figure 4. The serpentine pattern on a small scale puck test and picture of completed puck. Spacing of the wire segments was approximately 50 mm.**

Unaltered coal-tar sealant was too thin to adequately cover the wiring. It was determined that an additive would be required to thicken the sealant and increase its ability to cover. The first additive tried was fine-grained silica sand. The sand was added to the sealant at a rate of 118 g of sand to every 500 mL of sealant. This adequately thickened the sealant to cover the wiring (Figure 5). The addition of sand also caused the sealant to crack upon drying. Through consultation with Mr. Ray Bonaquist of Advanced Asphalt Technologies, it was determined that hydrated lime could serve as a substitute thickening agent. The second test added 141.7 g of hydrated lime to approximately 500 mL of sealant. This increased the sealant's viscosity to the point that it could not be spread. With lower quantities of lime, the sealant could be spread but it became brittle upon drying, with the surface discolored by a white residue. As a result of these problems, the decision was made to use silica sand instead of hydrated lime.

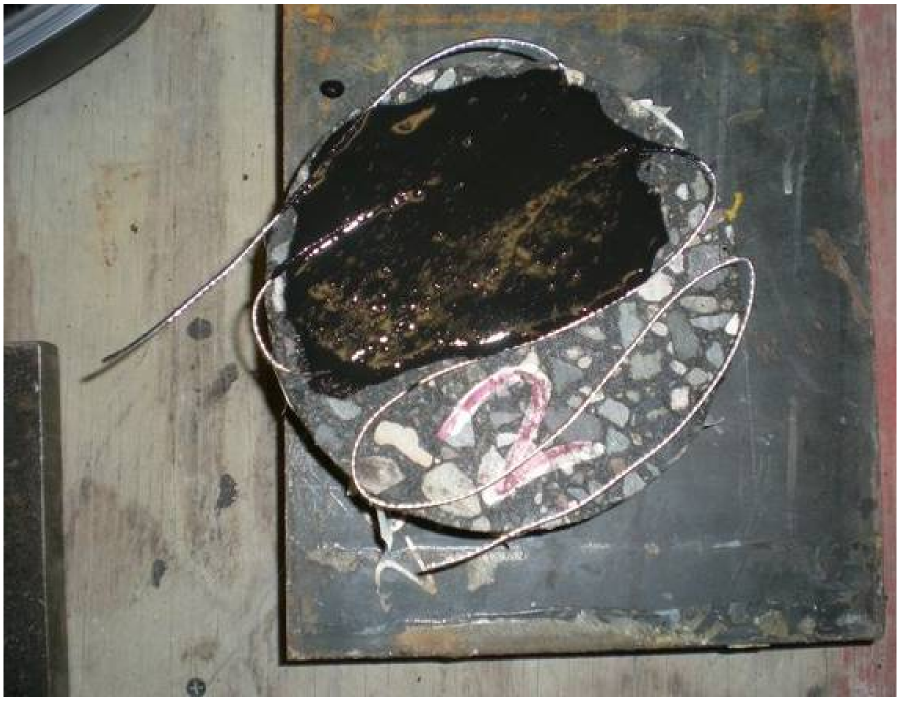

**Figure 5. A puck being covered with a thick layer of sealant to cover the wires.**

Initial tests used the train transformer to apply a constant voltage of 10V across the puck for 30 minutes at room temperature. Temperature was measured with an infrared thermometer at four locations on the specimen (Figure 6). As shown in Figure 7, temperature increased with time at all locations and stabilized at an average temperature increase of 36.45°C. There was some variation in the temperature increase at the different points, however. This was most likely caused by the distance between the measured point and the embedded wire. Temperature measurements taken in close proximity to the wire were generally higher than those taken further from the wires. This indicated that the seal coat has low thermal conductivity, such that heat does not distribute evenly.

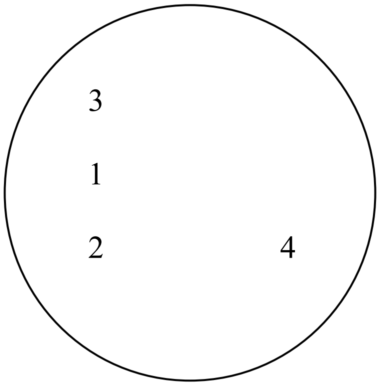

**Figure 6. Different points were measured for temperature changes for the small scale puck test. Puck diameter = 300 mm.**

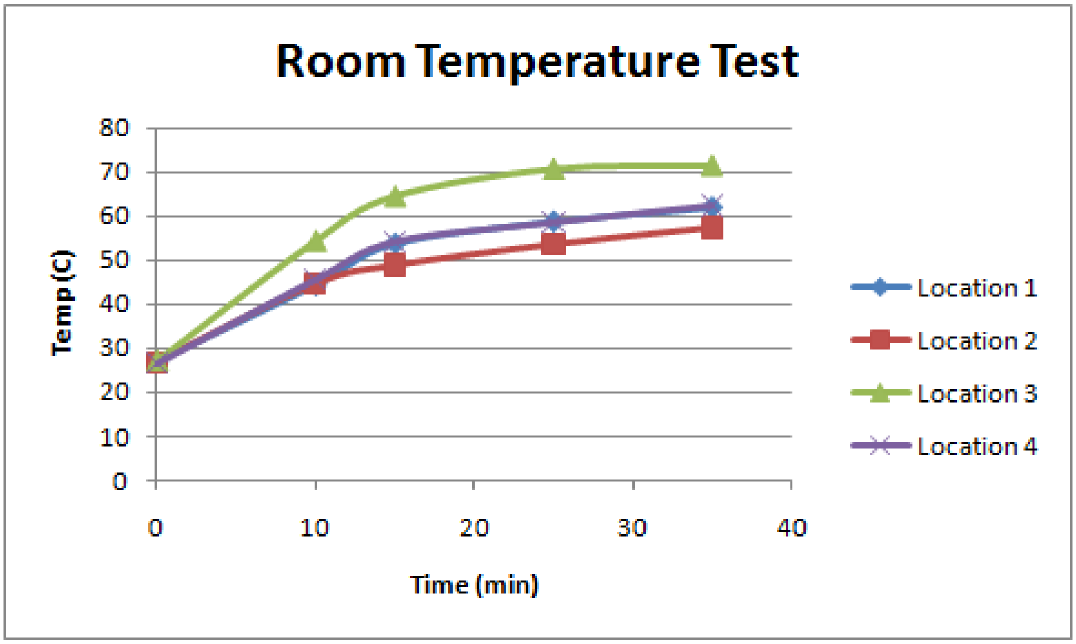

**Figure 7. The change in temperature (C) over time (min) for the small scale pucks at room temperature.**

The next test served as a laboratory scale proof-of-concept for the snow melting system. Two similar asphalt pucks had their flat surface covered with ice at room temperature. A puck with just a layer of sealant without a wire underlay was used as the control, while the other had the sealant and wire based heating system installed. Connected to the transformer and running at 10V, it took 10 minutes to melt all of the ice from the test sample, while the control still had a visible and significant quantity of ice remaining. This affirmed that a system utilizing resistance heating wires under sealant could generate sufficient heat to melt snow.

To determine if the temperature increase was consistent at colder temperatures, the test sample and control were placed in a laboratory environmental chamber (Test Equity 1000 series Temperature Chamber) at a controlled temperature of -12°C. Using the train transformer, a constant 10V was applied for approximately 35 minutes. The test sample increased from an initial average temperature of -9.55°C to a final temperature of 24.1°C, a change of 33.65°C (Figure 8).

In a second environmental chamber test, 636.6 g cylinders of ice were placed atop the test sample and the control specimen. A voltage of 10V was applied to the system; this correlated with the maximum current of 5A possible from the transformer. The temperature in the environmental chamber was maintained at -12°C through the test. After one hour of current flow, the ice atop the test specimen had decreased in mass to 419.8 g. The control did not show any signs of ice loss due to melting or sublimation.

Approximately 220 g of ice melted in an hour. Using the latent heat of water, the total energy used to melt the ice was $7.24 \times 10^4$ J. Based on the area of the puck and the test duration of 3600s, the energy use of our system is approximately $1.8 \times 10^5$ J. The efficiency of the system was approximately 40%, which was lower than the 50% estimated by our theoretical calculations. This recorded measurement was close enough given the many simplifying assumptions and approximations in the theoretical calculations.

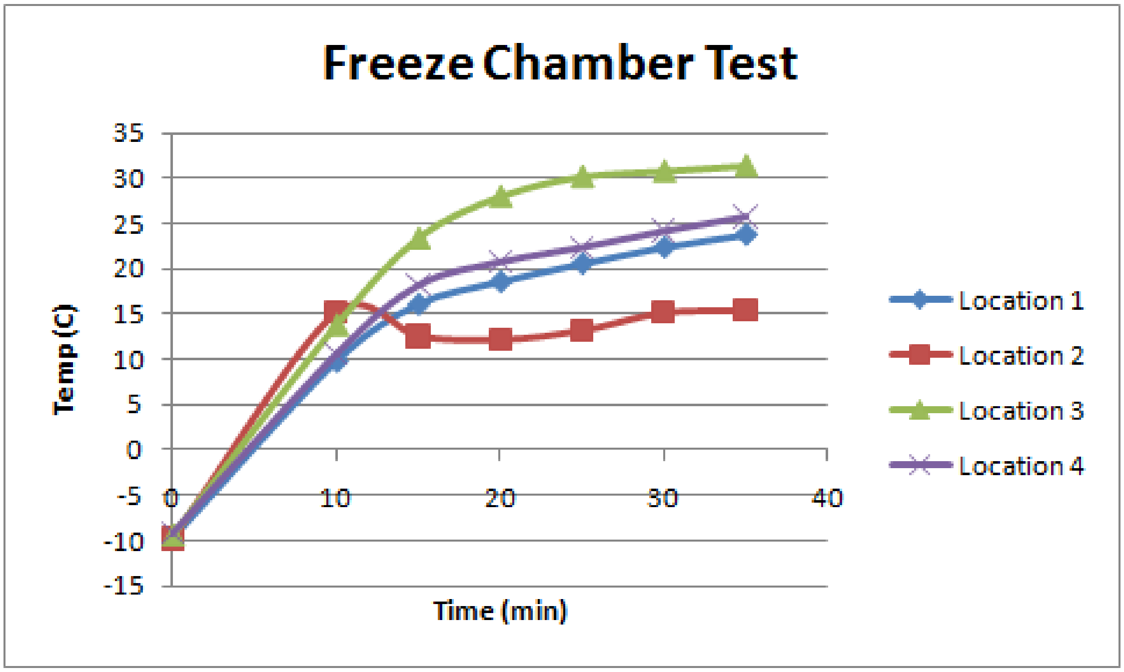

**Figure 8. The change in temperature (C) over time (min) for the small scale pucks in the freezer chamber**

This series of tests showed that nickel chromium wire and sealant combination was a viable system for melting snow at temperatures comparable to a winter environment. Based on these results, a full-scale test of such a system could be justified.

### *Large Scale Evaluation*

Based on the results of the small scale testing, it was possible to expand to large scale trials. Two variations were tested. The first was a field installation, meant to test the heat dissipation characteristics of such a system. The second would be divided into two modular test sections, which could be used in a controlled environment to both help optimize the design, as well as determine the efficiency of the system.

### Parking Lot Testing

The laboratory scale experiments demonstrated the feasibility of the concept. Large scale testing to evaluate the performance of key system components was the next logical step. Experimentation was expanded to an outdoor section the size of a parking lot space. Designed to prove the system's viability on a residential scale under real-world conditions, the large scale outdoor test was also designed to compare the efficiency of the system with the theoretical estimates. The test was conducted using a parking space located in Parking Lot EE, outside the Engineering Laboratory Building (Bldg. 089) at the University of Maryland – College Park. The space had a north-south orientation, with the southern end abutting a large laboratory building. Figure 9 and Figure 10 show the test area on the campus and the actual test site. The test area measured 2.44 x 2.44 m.

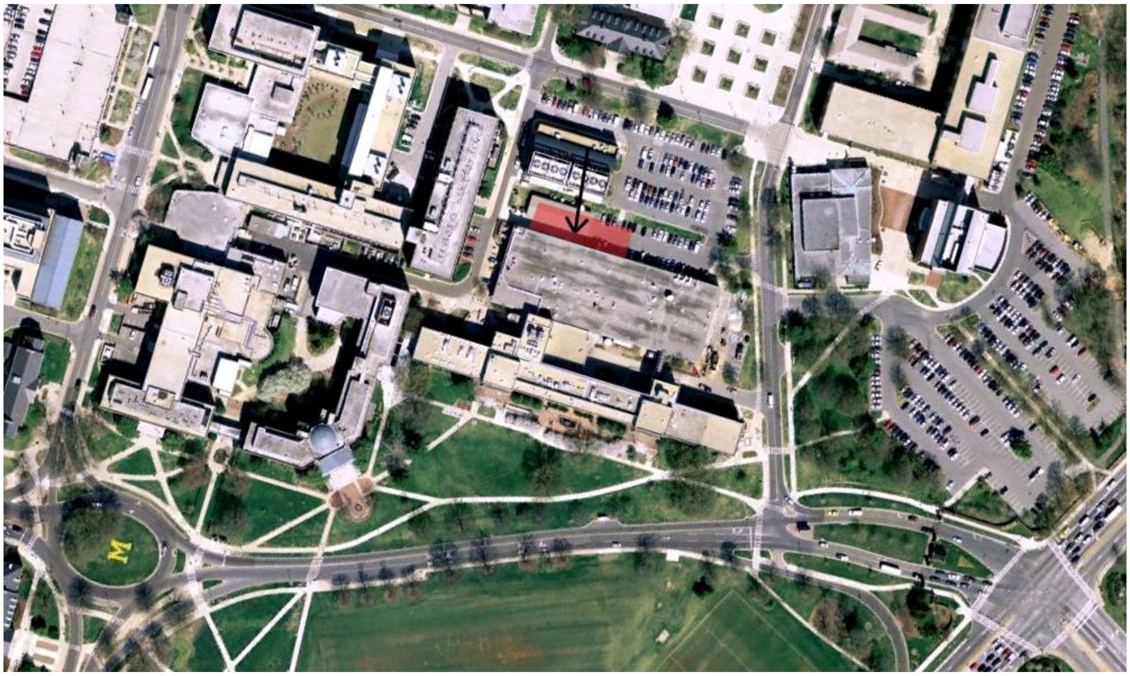

Figure 9. The location of the parking space relative to campus.

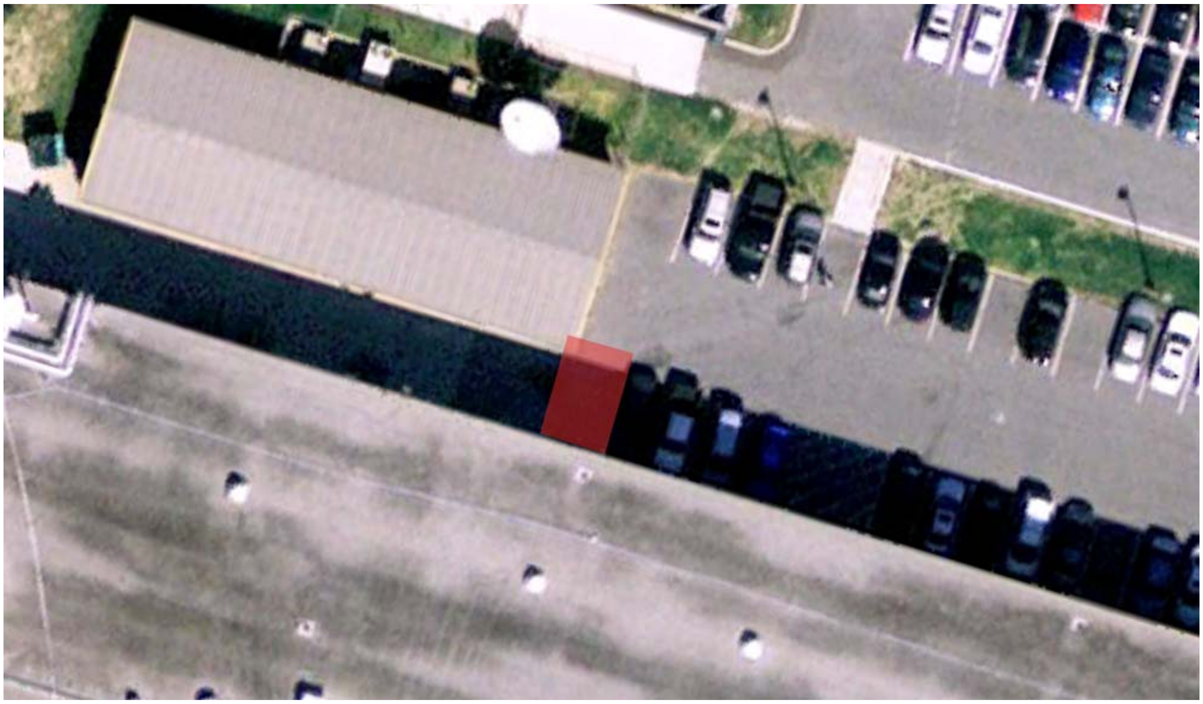

Figure 10. The actual space in the Glenn L. Martin Hall parking lot.

The design of the test area called for a grid of Nichrome wire affixed to the surface of the pavement using driveway sealant. The first step in the test was to design the grid geometry and determine its power characteristics. Laboratory tests helped to determine the optimum wire spacing. A total of 66cm of the 18 gauge Nichrome wire was used for the spacing test. The wire was shaped into a horseshoe; with the two ends spread 13cm apart as shown in Figure 11.

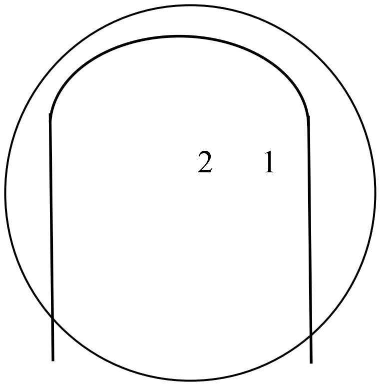

**Figure 11. Horseshoe wire design on asphalt puck. Location 1 is located 2.5 cm from the right edge of the horseshoe. Location 2 is located 2.5 cm from location 1.**

An infrared thermometer was used to measure how far the heat was spreading from the wires (Figure 12). Unfortunately, little spreading of the heat through the sealant was observed. After 30 minutes, the temperature of the sealant located 2.5 cm from the wire only heated up 3.2°C compared to the 27°C increase of the wire. As a result, a maximum of 5 cm between wires was selected as the design spacing.

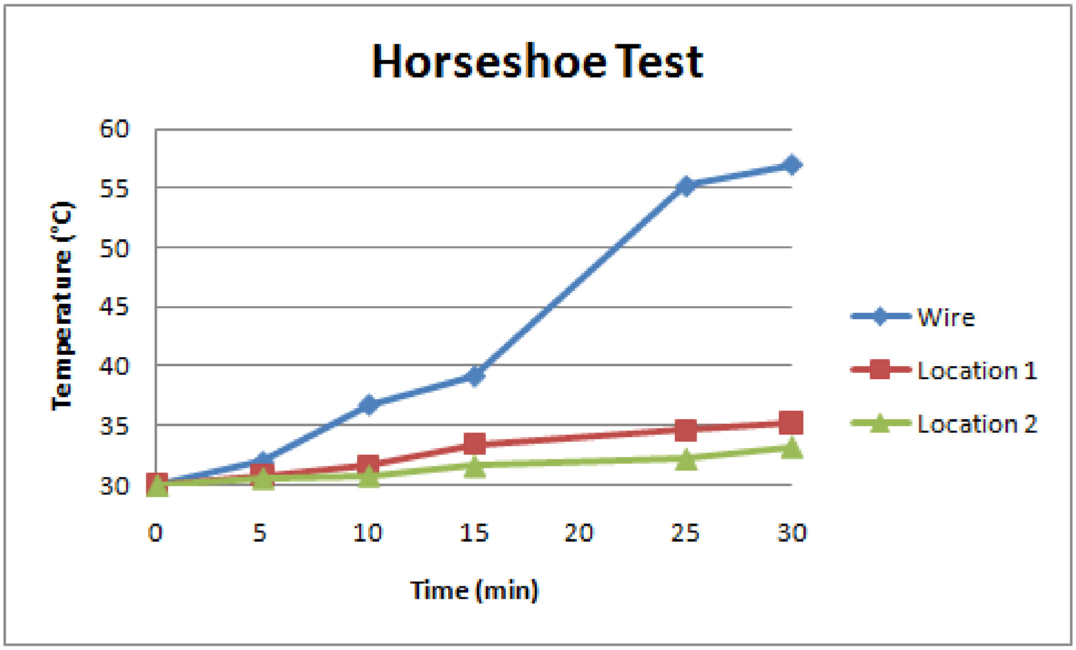

**Figure 12. Change in temperature of location 1 and 2 compared to temperature change of wire.**

Safety was a primary concern in the design of the full-scale test section. Since wires may potentially become exposed as the sealant wears, the system voltage needed to be lower than the OSHA limit of 50 volts. As such, the system was capped at 20 volts, to provide an additional margin of safety.

The large scale field test required a different type of wire than used in the small scale laboratory tests. As the system was originally intended for residential applications, the wiring needed to be affordable. Initial laboratory testing used 18 gauge Nichrome wire, an 80% nickel and 20% chromium alloy. To reduce cost, the field implementation would use a 22 gauge wire, made of an alloy of 60% nickel, 16% chromium, and 24% iron. The wire was cheaper due to the smaller percentage of nickel and chromium, both of which are more expensive than iron. Costs of the 80/20 alloy were approximately $62 for 200 linear feet, while the costs for the 60/16/24 alloy at 22 gauge was $48 for 200 linear feet.

The design of the full-scale field application was confirmed using PSpice, a standard software package that simulates electrical circuits. The circuit design in PSpice is depicted in Figure 13. Further details of this digital model can be found in

Appendix A. **Additional Figures and Accrued Data**The shorter horizontal resistors represent the Nichrome heating elements, while the long, undulating wires represent the busses to which they are attached. The target resistance of the system was .2Ω. This came from OSHA regulations that kept the system to a low voltage of 20V with a current of 100A. The high current was used to ensure a proper heating of the wire, using a power density of about 2000W. Calculated using Ohms Law, a target resistance of .2Ω would satisfy the requirement of a low voltage system. Assuming a test section of approximately $6m^2$ the total power requirements would be $333W/m^2$. This analysis confirmed that a design similar to this would provide the required resistance and power dissipation.

To generate this amount of power, two RP-36-25 RectiZpower transformers from PowerVolt Inc. were purchased (See specifications in Appendix B). Each transformer is capable of producing up to 50 amps of current at 18V. When connected in parallel, the total current capacity is 100 amps. To confirm whether or not the transformers could be operated in parallel, two inexpensive Radio Shack 3V 3A transformers were used for a trial. The total current output was 6 amps, confirming the theory.

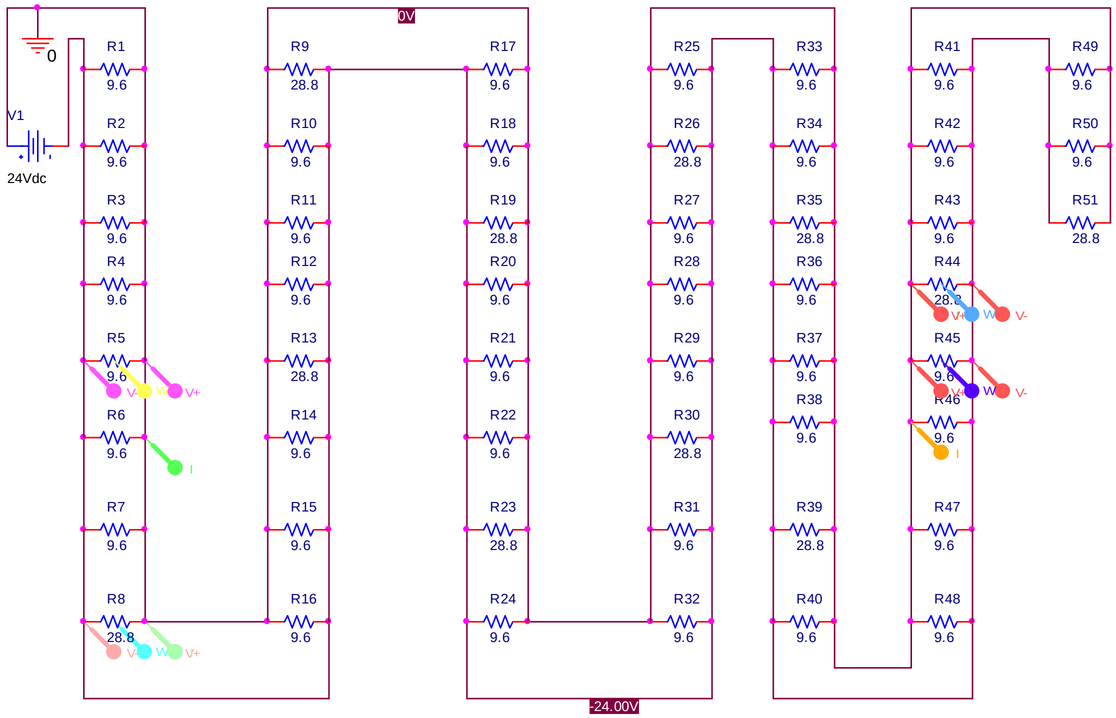

**Figure 13. The PSpice circuit analysis conducted to determine the configuration of the large scale test.**

A parallel circuit is needed to provide the low overall resistance required by the test system. This circuit was composed of two copper-stranded busses running the length of two parallel edges of the system (Figure 14). These busses distribute power to the parallel branches of Nichrome wire. To meet the target total resistance, every fifth Nichrome branch was made triple the length of the other wires, but still only connected to the busses at its ends. Each of the regular wires had a resistance of 9.6 ohms while each of the tripled wires had a resistance of 28.8 ohms. There were a total of 40 regular wires and 11 tripled wires.

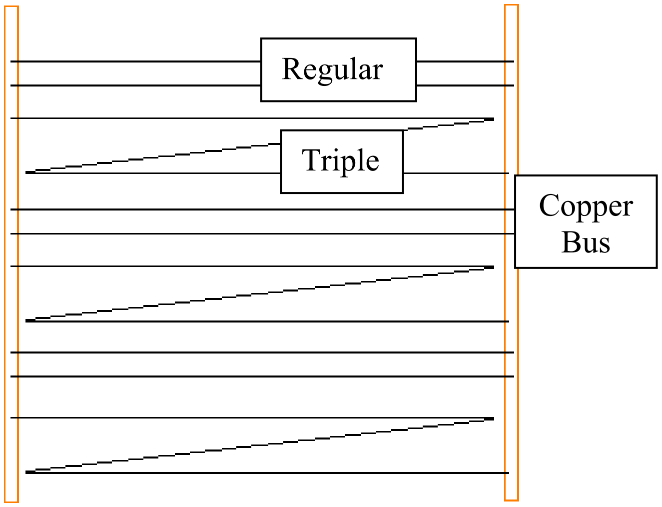

**Figure 14. The large scale parking lot model consists of 2 copper busses running down the parking space. In between the two busses are 40 straight wires (9.6 Ω each) and 11 zig-zag triplet wires (28.8 Ω each)**

The total resistance $R_{total}$ of the circuit can then be calculated as:

$$\frac{1}{R_{total}} = 40\left(\frac{1}{9.6}\right) + 11\left(\frac{1}{28.8}\right)$$

$$R_{total} = 0.217\Omega \tag{4}$$

Construction of the system began over a weekend in late February 2008. Purchase of materials and shipping delayed the construction time, but the warmer-than-average winter allowed for a later system build. Due to the lack of experience with building such a system, initial progress was slow. Figure 15 shows the construction of the wire grid. During the installation, keeping the wires flush with the pavement became a problem and several methods were tested to address the issue.

**Figure 15. Placing wires on the parking space before covering with sealant (left). Masonry nails were used to hold the Nichrome wires on the pavement (right).**

The uneven pavement surface on which the system was being installed made it impossible to use the weight of the sealant to hold down the wires as the sealant dried. Initial plans were to use staples to hold the wires to the asphalt until they could be sealed in place. However, the lightweight staple gun tried for this was unable to penetrate the asphalt. A second attempt using larger electrical staples hammered into the asphalt also failed. Finally, ¾" masonry nails with washers (Figure 15) were used successfully to tack the wire in place until the sealant dried.

Three coats of sealant mixed with sand were needed to completely cover the wires (Figure 16). This was due to in part to the irregularity of the pavement surface. Another problem was that the sealant cracked during curing, a problem that persisted despite multiple coats using both sand and hydrated lime as an additive. In addition, a few of the masonry nails did not hold in place, allowing the wires to pop out of the sand-thickened sealant as it slowly dried.

**Figure 16. The completed sealant on the parking space before drying.**

Due to delays in shipping, only one transformer had arrived in early March, when construction of the system was completed. Since the system was designed for a 20V/100A power source, one transformer putting out 50A would be inadequate. This was confirmed by actual testing on the field section. The measurement of the actual resistance of the system was .217Ω, which corresponded to our target of .2Ω. The actual voltage for one transformer was 16.5V compared to the 20V in the calculations and the amperage was 55A, which was more than the rating of 45A. As the rating is only a recommended limit to prevent damage, it is possible for the transformers to supply more than the rating. Due to the inadequacy of one transformer, though, field testing was delayed until the second transformer arrived.

The second transformer arrived on April 20th 2008, too late to test with natural snowfall. The warm temperatures further made any kind of accurate measurement of snow or ice melting volume impossible. As a fallback, a FLIR infrared camera was used to determine the heat output and dispersion characteristics of the system (Figure 17). The use of the camera was graciously donated by the Federal Highway Administration and operated by Dr. Nelson Gibson on behalf of the team.

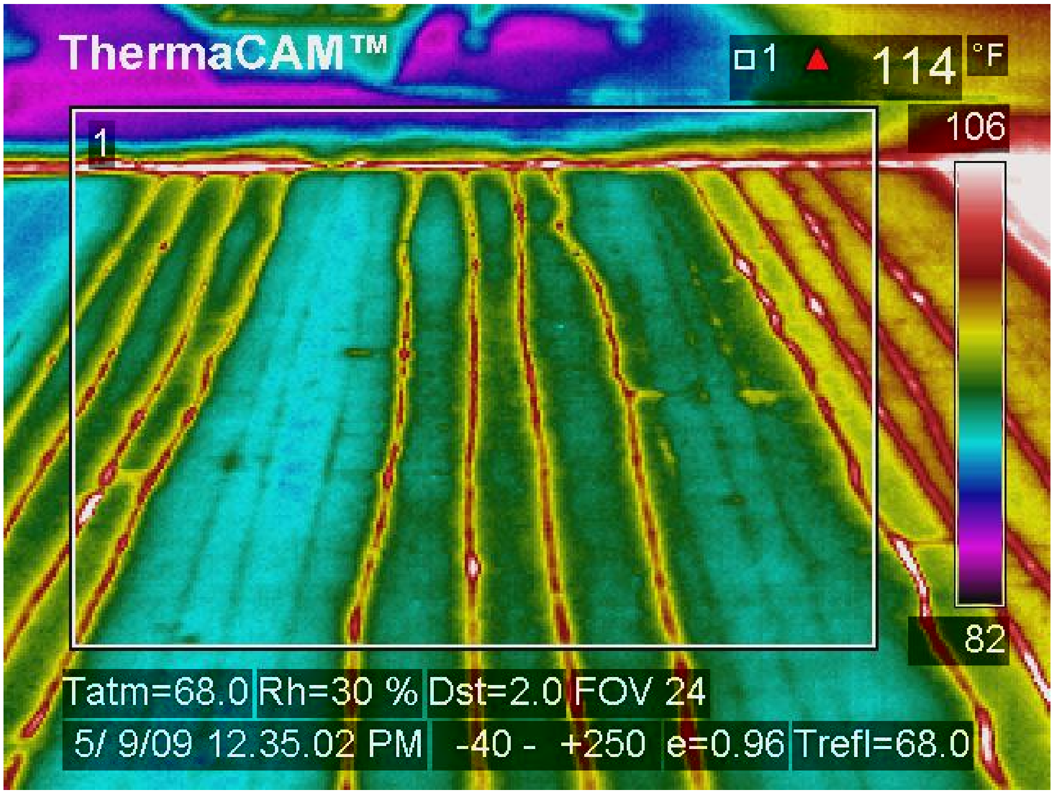

**Figure 17. Thermal image of the pavement after system was turned on. The legend on the right side of the picture is the temperature in °F. The temperatures increase suddenly on the right side due to sunlight shining on the pavement and warming it up.**

The images display the various temperatures as different colors, ranging from 82°F to 106°F. According to the legend, the pavement was around 90°F. The wires heated up to around 100°F with some hot spots around 106°F. The pavement was warmer on the right side where it was exposed to sunlight. The camera showed uneven heating of the pavement surface.

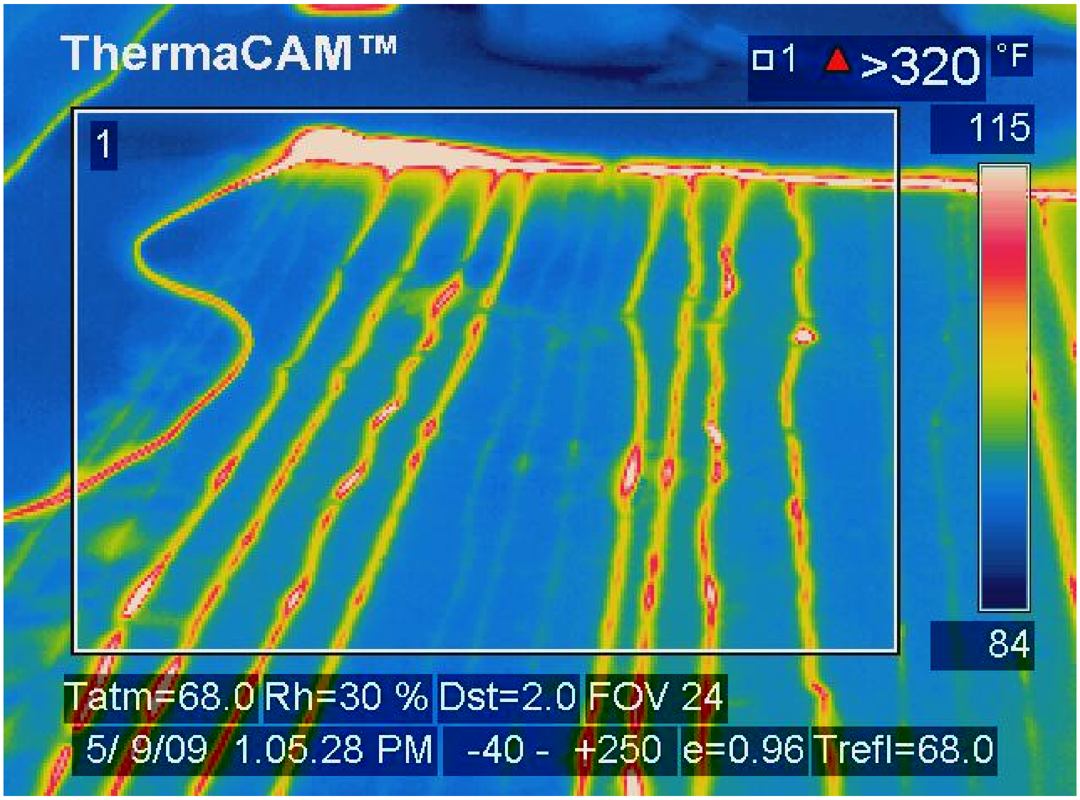

**Figure 18. Section of sunlight testing where the single wires in yellow and red have much more heat than the cooler wire areas shown in between in blue.**

The area directly adjacent to the straight wires heated significantly, but the heat did not spread beyond that. The tripled wires, though necessary for the electrical specifications of the circuit, were ineffective at generating or dispersing heat. A control picture was shown for determining the heating difference between the pavement in the sun and shade. Figure 19 illustrates the temperature difference between the cool, black section in the shade and the warmer green and blue sections in direct sunlight.

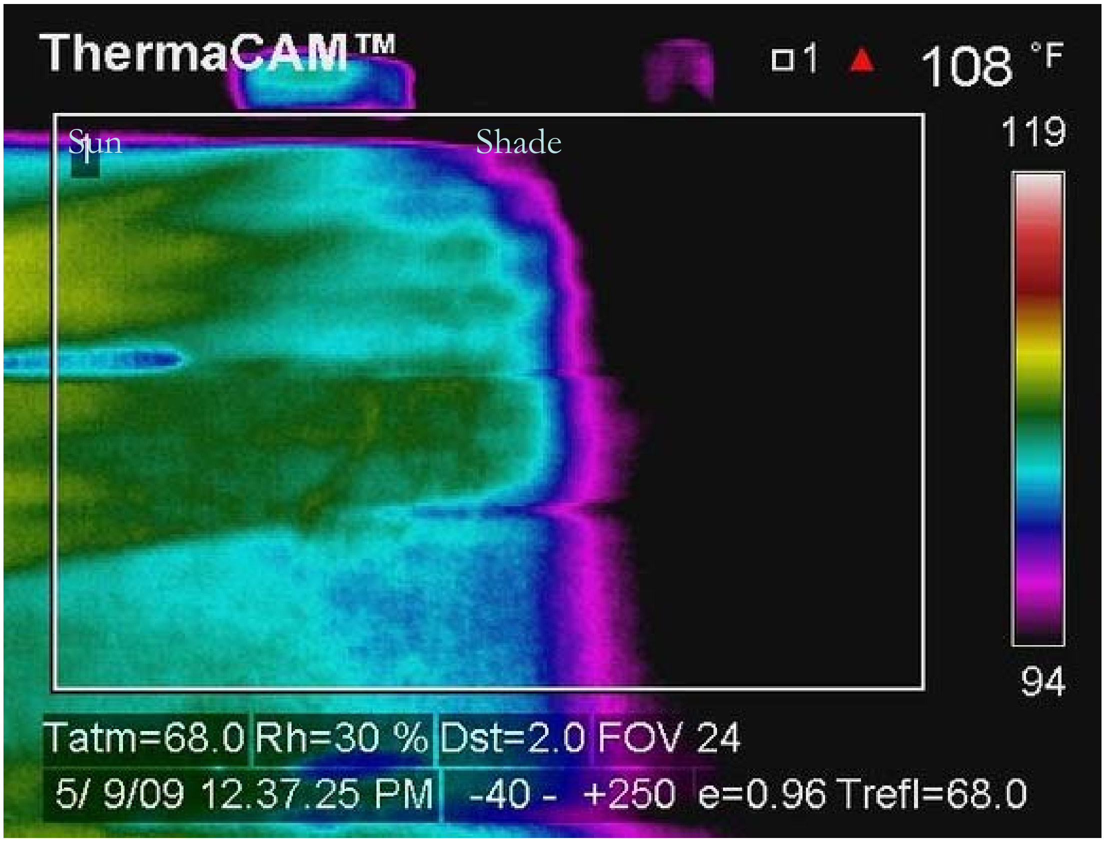

**Figure 19. The control image between the pavement in the sun and shade.**

After taking images and temperature measurements, the data was quantified to see how much difference the system made to the overall temperature of the pavement. As shown by Figure 20, the differences in the full sun test are small, showing relatively low amounts of heating. However, the shaded test showed a larger gap in temperature difference between the testing section and the control. As the system was intended to be run in the snow, where there is less direct sunlight, the results were promising for the system and the shaded results were looked at more carefully as proof of operation of the system.

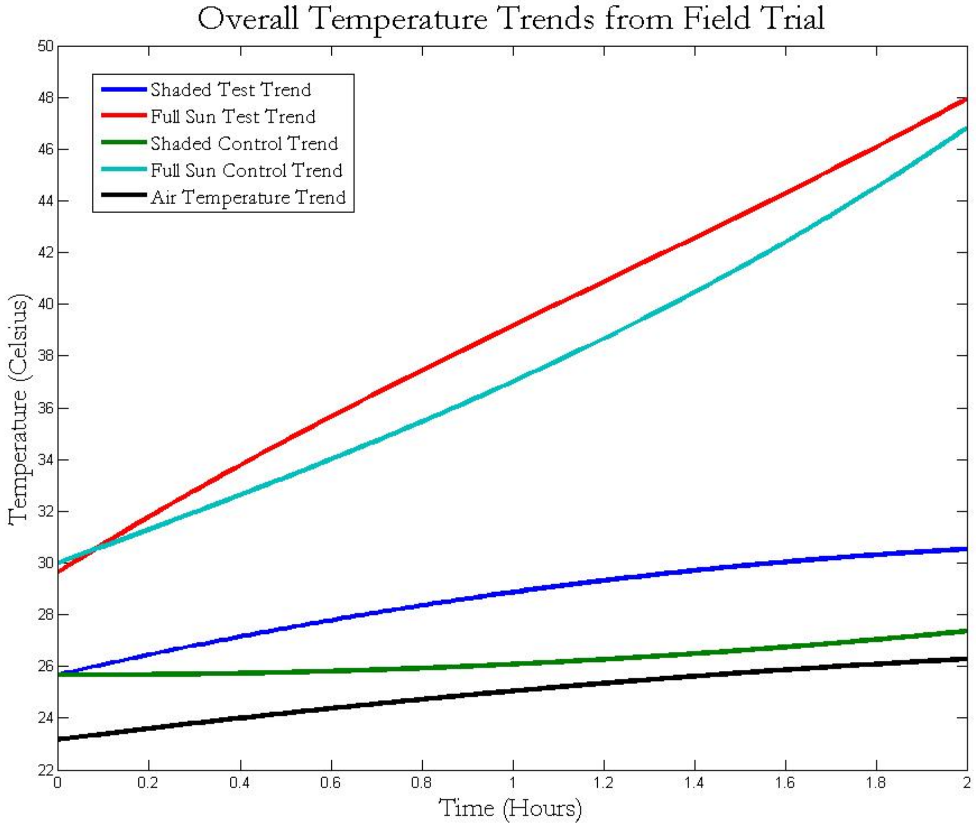

**Figure 20. The overall outdoor testing of the shaded and sun test sites and control trend.**

The principal problem of this large-scale field test was the inability to effectively evaluate the efficiency of the system without any snow to melt. An additional problem revealed by these tests was the inefficiency of the sealant as a heat transfer mechanism. The infrared camera showed the system did indeed produce heat immediately around the wires. As shown in Figure 18, the red and yellow areas of high heat are where there are single strands of wire. The blue section in the center of the image is a much cooler section where a triplet wire was placed.

This indicated a few potential improvements for a second set of large-scale testing. As the heat did not dissipate effectively across the pavement surface, the heating elements should be spaced closer together to make the melting process more efficient.

Furthermore, the design should be altered to eliminate the tripled wires, as these proved incapable of generating sufficient heat. The initial testing also showed that connecting the wires to the busses with conductive tape was inadequate, as the wires soon separated due to fraying of the stranded copper busses. Consequently, the Nichrome wires should be soldered to the copper busses to prevent degradation of the connection over time. A thicker sealcoat should also be used to adequately protect the wires. These improvements were incorporated into a second large scale test effort.

### Freezer Testing

This section outlines the second large scale test, which was conducted in Fall 2009. Due to the time constraints of the academic year, it was infeasible to wait to test using natural snowfall during the winter. Therefore, a portable large-scale system that could be tested in a climate-controlled space was constructed. This portable version was used to quantify the overall efficiency of the system, to analyze the differences in efficiency due to wire spacing, and to evaluate the improvements made since the first large scale test.

Work on the second test begun in the fall of 2009. The test sections were designed as two separate modules, both for ease of transport and to allow the simultaneous testing of multiple potential configurations. Taking into account the results from earlier tests, several improvements were made to the new test sections. Heavier 8-gauge stranded copper wire was used for the bus and, unlike previously, only small sections of insulation were removed for the electrical connections. The change was in response to the durability issues encountered with the exposed copper wire stripping down the sides of the test area in the parking lot tests. Furthermore, connections between the copper busses and Nichrome heating elements were soldered to ensure a proper electrical circuit. Lastly, all busses were secured with large masonry nails before making the wire connections.

The poor heating performance of the triples also required that the circuit be redesigned. Heavier gauge Nichrome wire was used as to increase the resistance per unit length. A thicker sealant was also required to ensure that all wires were covered properly. In addition to making the system more durable, the thicker sealant provides an added safety margin to ensure that all wires remained embedded in the pavement and not protrude from the seal coat.

The two modules were different sizes, one measuring about 0.61m x 2.44m (2 x 8 ft.) and the other 1.22m x 2.44m (4 x 8 ft.) (Figure 21). Both panels were designed to use 25 Nichrome wires from bus to bus, the larger panel used wires spaced 5cm apart while the smaller grid had wires spaced at 2.5cm From theoretical calculations completed during the design process, both panels had an ideal resistance of .131 ohms. In practice, the panels were measured to have a resistance of .2 ohms +/- .05 ohms. Derived from theoretical calculations mentioned previously, the target power density for each panel was .0323 W/cm$^2$ (30W/ft$^2$). The difference in wire spacing between the large and small panels was designed such that two different power densities could be tested for effectiveness in melting snow and to verify theoretical calculations. The large panel, with 5cm wire spacing, had a power density of .0194W/cm$^2$ (18W/ft$^2$) while the smaller panel, with 2.5cm wire spacing, had a power density of .0398W/cm$^2$ (37W/ft$^2$). Each individual wire served as a heating element, and were connected to the buses, creating a parallel circuit configuration in which total resistance decreases as the number of resistance elements increases. The total panels can then be viewed as a single resistance element with an equivalent total resistance. When the panels are connected in series, the total resistance of the circuit is the sum of the total resistance of the two panels. In theory, this resistance was calculated to be .262 ohms. However, the measured resistance of the two panels in series was .4 ohms, with a measurement accuracy of +/- .1ohms.

**Figure 21. The test panels in the freezer. The smaller panel is on the left and the larger one is one the right.**

The sections were constructed atop frames of Douglas fir No.2 2x4 studs. Each frame was then sheathed on one side in ½" (1.27cm) plywood. A layer of 3/8" (0.95cm) Duraroc cement board was then screwed to the top of the plywood. The copper busses were affixed to the edges of the board along the long axis, and then soldered to the Nichrome branches using acid core solder. Electrical tape was used to hold down the wires prior to spreading the sealant (Figure 22). A thicker sealant (SealMaster Polymer Modified MasterSeal, see specifications in Appendix B was then used to coat the panels (Figure 22). Unlike a hardware store sealant that contains 40% solids, this sealant contained 60% solids, resulting in a heavier and more durable application. However, the panels still experienced minor cracking of the first coat, which was allowed to cure for 24 hours before a second coat was applied. The cracking was still apparent even after the second coat. One presumption is that this is due to the sheer amount of sealant needed to cover the wires, leading to uneven drying and thus, cracking. Another is that the cracking related to the amount of electrical tape used to hold down the wires. On this basis, the use of electrical tape was minimized in the construction of the second panel. Though this did not entirely eliminate the problem, the subsequent operation of the system did not appear to be affected by this cracking.

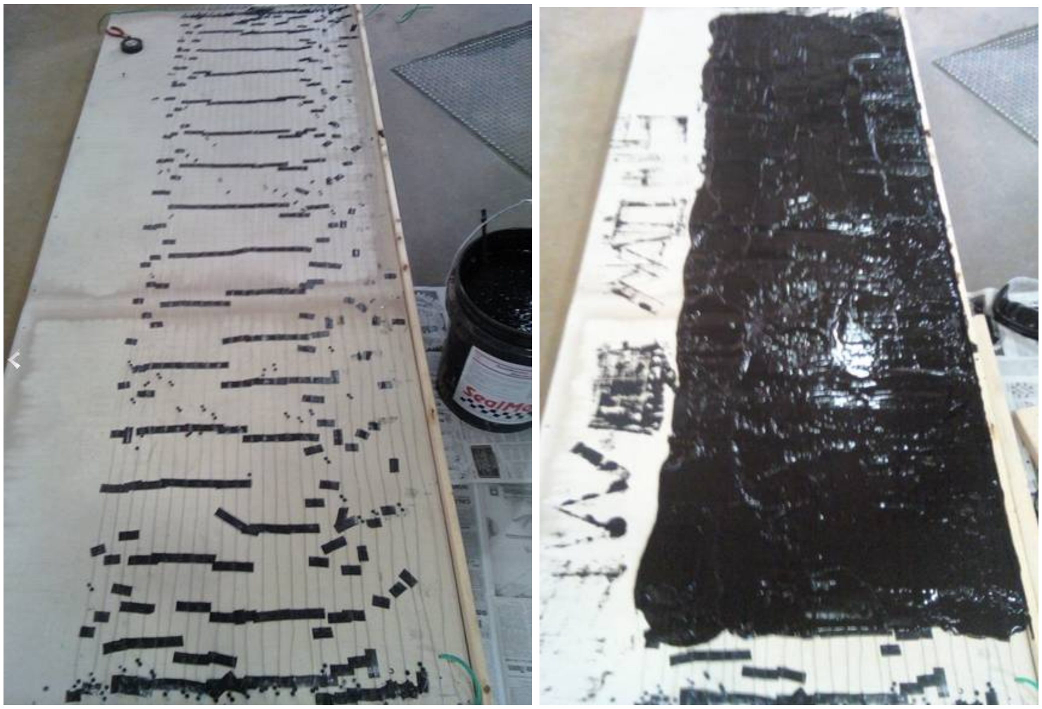

**Figure 22. Construction of the panel. Electrical tape (left) was used to hold down the wires.**

Initial searches for a testing location were unsuccessful, as commercial cold-storage facilities were unwilling to provide access for research use. However, the Dining Services department at the University of Maryland was willing to provide freezer space in which to test. While this provided a number of potential locations, it also meant that the testing schedule would have to accommodate foodservice concerns. Eventually, though, an empty freezer of sufficient size became available in Cole Fieldhouse at the University of Maryland.

The freezer contained both a refrigerated antechamber and a full size freezer. Both panels were placed in the freezer portion, which was kept at an ambient temperature of -4.44 $^{o}$C. Once placed, both panels were hooked up to the power supply. Measurements were taken at numerous locations (Figure 23) on the panels over the course of one hour to establish equilibrium conditions at the start of the test (Figure

24 and Figure 25). The locations were distributed over different regions of the panel to determine any temperature variations with the heating of the system.

These measurements showed a general warming trend across all locations on both panels. However, there were some anomalous data points that did not fit with the trend. The most likely source of this is measurement error due to inaccuracies with the infrared thermometer. It is also possible, though, that this resulted from the irregular circulation of air on the underside of the panel, leading to uneven heat distribution. On average, the large panel showed an approximate warming of 12°C over a 45 minute period, and the large panel showed an approximate warming of 15°C during the same timeframe.

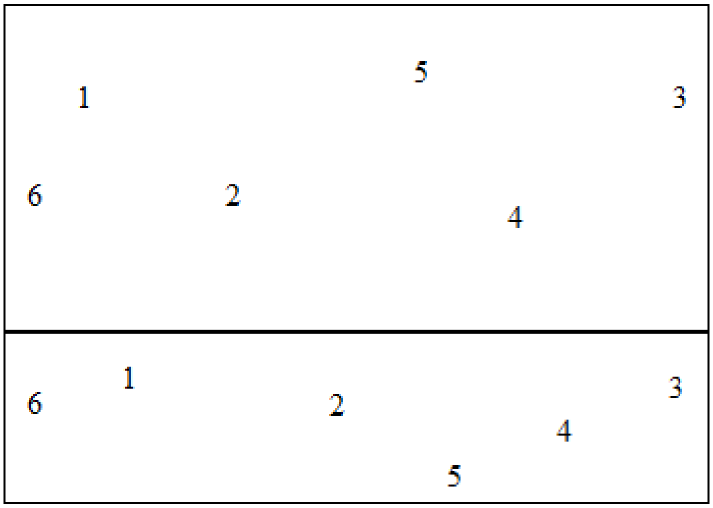

**Figure 23. Locations where temperatures were measured on the larger (top) and smaller (bottom) panel. Points 1 and 4 are between wires. Points 2 and 5 are on wires. Points 3 and 6 are on the buses.**

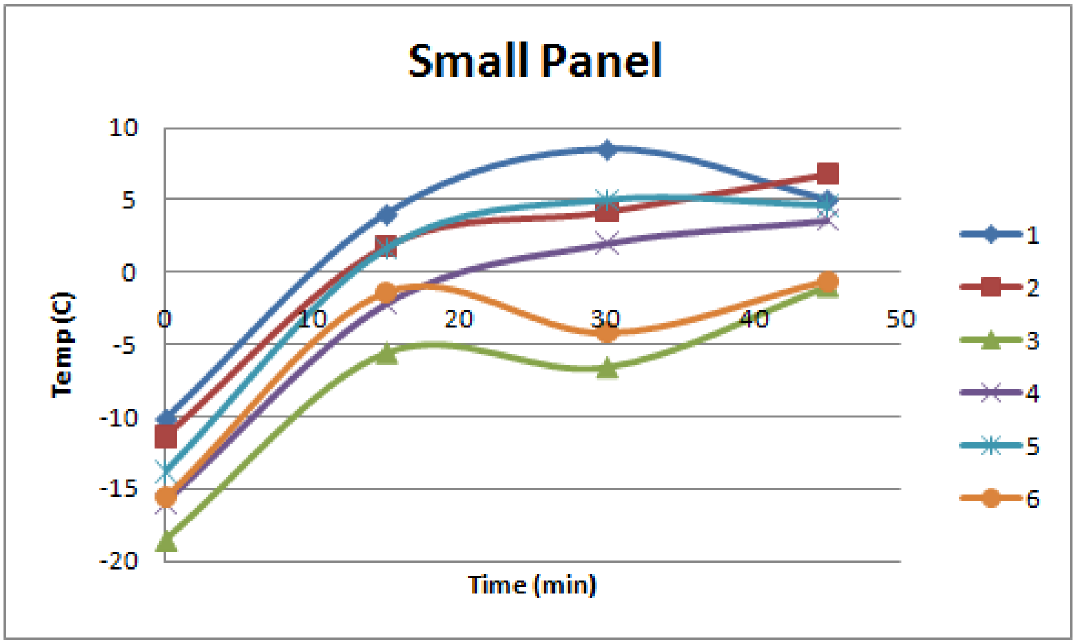

Figure 24. The preliminary test without snow on the small panel in the freezer.

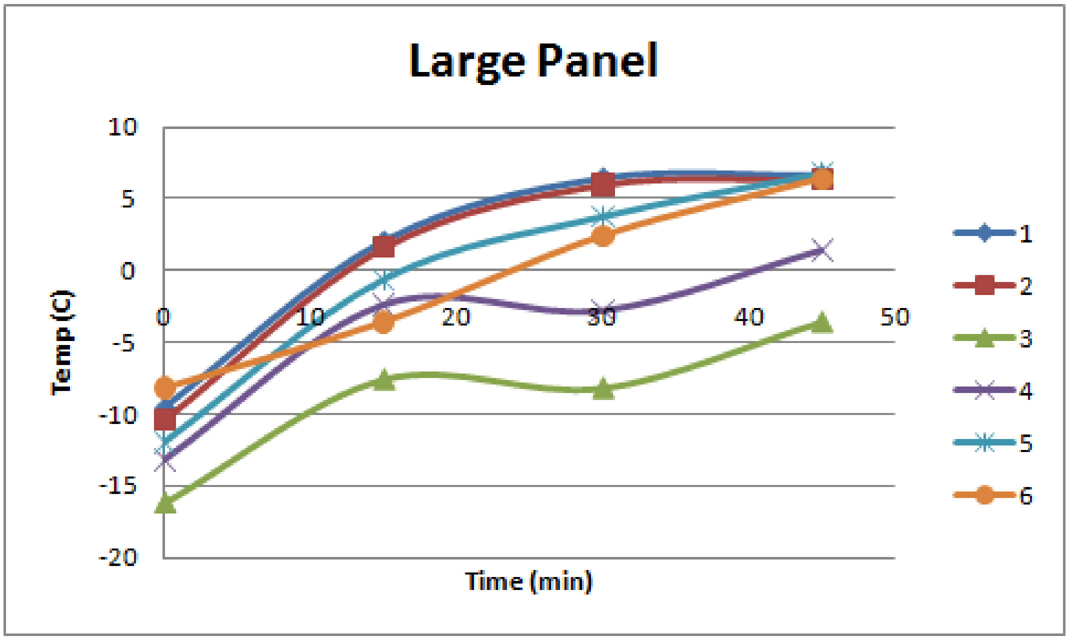

Figure 25. The preliminary test without snow on the large panel in the freezer.

After the initial temperature recordings were taken, a layer of crushed ice roughly 2.54cm (1 inch) thick was placed on each panel to simulate snowfall. A control amount of ice was placed in a plastic container away from the heat of the system.

While a full-size, unheated panel would have been preferable for a control, the limited amount of space in the freezer made this impossible. As such, the small-scale control served as a representative sample. Photographs were taken of the ice-covered system over the course of four hours (Figure 26 through Figure 31) The ice layer showed significant melting at the first fifteen minute check (Figure 27). This is indicated by the horizontal banding occurring on the larger panel, as well as the general reduction in ice coverage pictured on the smaller panel, which can be distinguished by the white-grey band along one end. The ice appeared to melt at a relatively constant rate during the four hour period, with the smaller panel being effectively clear of ice by the end of the time (Figure 30). This was in line with the hypothesis that the smaller section would melt ice at a more rapid rate with wires spaced closer together. The control specimen of ice did not show any signs of melting throughout the four hours the system were run in the freezer (Figure 31).

Figure 26. The panels covered with ice at the start of testing.

Figure 27. The large panel after 15 minutes of run time. Notice the banding pattern of melting caused by the wire spacing.

Figure 28. The large panel after an hour and a half. Notice the puddle of water forming from melting of the ice. The control in the plastic container on the right has shown no signs of melting.

Figure 29. Both panels after 2 hours. The smaller panel has almost melted all the ice and the larger panel has melted a significant portion shown by the puddle forming at the top left of the photograph.

**Figure 30. The smaller test section (left) has almost all the ice melted at the 4 hour mark. The large panel (right) at the same time has much of the ice melted off the pavement.**


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**Figure 31. The control amount of ice after the entire four hour period. Much (if not all) of the ice remained after testing.**

Since all the ice melted from the smaller section, the efficiency can be calculated by comparing the energy consumed to melt the ice to the energy supplied by the system. The energy used to melt the ice was calculated using the mass of ice and latent heat of water. The total mass of the ice was calculated by the density of water and the total volume of ice. Total volume of 2.54cm of ice on a 0.61m x 2.44m (2x8 ft.) surface is .41$m^3$ (1.33 $ft^3$). The total mass of ice is $3.78 \times 10^4$ g. Multiplying by the latent heat of water makes $Q = 1.26 \times 10^7$ J. One transformer supplied energy to the smaller panel. As a result, the total energy supplied by the 16.5V/55A system over the 4 hour test duration was $1.31 \times 10^7$ J. The computed system efficiency under below-freezing conditions thus is 96%.

This calculated efficiency is high for a few reasons. The 2.54cm (1 inch) ice thickness measurement was a rough estimate. Parts of the small panel were not covered with ice, particularly the around the edges. In addition, the total volume was not a solid block of ice. There were air pockets in the crushed ice layer. All of these factors would significantly reduce the total amount of ice melted. As such, a range of ice volumes were calculated, to demonstrate efficiency at different ice thicknesses (Table 8).

**Table 8. Efficiency values for a 16.5V/55A system running for 4 hours assuming different thickness values of ice**

| Thickness of ice | Efficiency |
|---|---|
| 0.635cm (0.25in.) | 24% |
| 1.27cm (0.5in.) | 48% |
| 1.91cm (0.75in.) | 72% |
| 2.54cm (1in.) | 96% |

Recall that the theoretical calculations underlying the system design had assumed 50% efficiency. The differences between the test panels and an actual installation suggest that the installed efficiency may be lower than this. Since the panels were spaced off of the ground, with a pocket of air trapped underneath, it is likely that the heat loss to the ground was lower than it would be with an on-ground installation.

In conclusion, the freezer testing indicated that a system was capable of melting a reasonable quantity of snow over a relatively short period of time under subfreezing temperatures.

### Large Outdoor Snow Tests

The winter of 2009-2010 saw record snowfall for the Washington, DC metro area, which allowed for the testing of the system under heavy snowfall conditions. The smaller 0.61m x 2.44m system was brought out to determine the capabilities of the system during realistic conditions. Since the small panel was not connected in series to the larger panel, the power through the smaller panel was effectively doubled. This results in a power density of .0796W/cm$^2$ (74W/ft$^2$). The outdoor temperature was -5.5°C at the time of the test, though the panel was at room temperature when brought out from the lab at the start of the test. The system was turned on when the panel had cooled to the outdoor air temperature and roughly 3.8cm of snow had accumulated on top of it (Figure 32).

**Figure 32. The SnowMelt system with fresh snowfall on the sealant before being switched on**

After about 25 minutes all the snow had melted off the testing panel (Figure 33). It was recorded that approximately 23cm of snow had fallen during the day, which can be averaged to find an approximate snowfall rate of 2.5cm/hr. During the test period, snow continued to fall heavily, but due to the heat produced by the system, no additional snow could be seen accumulating on the test panel. One can therefore conclude that the system was able to melt previously accumulated snow while simultaneously melting any that had fallen during testing.

**Figure 33. The system after running for 25 minutes with constant snowfall.**

The efficiency of this system can be calculated by comparing the power consumed to melt snow and the power generated. The energy used to melt the snow was calculated using the volume of snow, density of snow, and latent heat of water. The total mass of the snow was calculated by the SWE and the total volume of snow. Total volume of 3.8cm of snow on a 0.61m x 2.44m (2x8 ft.) surface is .61m$^3$ (2 ft$^3$). The total mass of snow is 5.66 x 10$^3$ g. Multiplying by the latent heat of water makes Q = 1.89 x 10$^6$ J. Using Eq. (3), the 16.5V/110A system generates 2.72x10$^6$ J over the 25 minute test duration. This makes the efficiency of this system under actual snowfall conditions 69%. This higher efficiency is likely due to the layer of snow beneath the panel. Like the air pockets in earlier testing, this insulated the panel from heat loss to the ground, making the efficiency higher than it would likely be in a real-world installation.

To confirm these results, 7.62 additional centimeters of snow were piled on top of the already heated system. After 2 hours, this 7.62cm of snow was melted by the system, as well as the additional accumulation from snow continuing to fall. After clearing, the system was left on for 20 more minutes, resulting in no accumulation.

Total volume of 7.62cm (3 in.) of snow on a 0.61m x 2.44m (2x8 ft.) surface is 1.22$m^3$ (4 $ft^3$). The total mass of snow is $1.13 \times 10^4$ g. Multiplying by the latent heat of water makes $Q = 3.78 \times 10^6$ J. Using Eq. (3), the 16.5V/110A system generates $1.31 \times 10^7$ J over the 2 hour duration. This makes the efficiency of this system 29%. The most likely reason for the lower efficiency is due to the fact that the snow was packed. As a result, the Snow Water Equivalent is probably higher than 10%. This means the system melted more snow than what was calculated.

The tests proved the concept behind the system, as well as general system performance. Performed in real-world conditions, this testing conclusively demonstrated the feasibility of melting snow using a resistance heating system meeting the aforementioned specifications.

### *Testing Conclusions*

The results from this testing show that the system successfully melted snow over small surface areas in a reasonable time frame. The system also meets the design requirement of retrofittability on existing pavements. However, the amount of power required to implement this system over an entire residential driveway is far too high for practical use. A typical residential electrical circuit can provide 2000W of power, while the system, covering only a space of 8ft x 6ft, dissipated 810W. Given perfectly ideal scalability, the system's size could only be increased by a factor of 2.5, resulting in a total area of 11.1m$^2$ (120ft$^2$). The system may therefore be most appropriate for smaller, high-priority spaces; these possibilities are discussed in the next chapter. In addition, durability issues need to be explored further. Though the initial outdoor section survived light vehicular traffic, the large scale panel systems were not exposed to traffic, leaving open the question of how long the systems will last with regular wear.

# Chapter 4: Discussion

This chapter discusses the testing performed during this study and provides insights into the design choices made by the team. The discussion will proceed chronologically from the first sealant tests through the final large-scale outdoor testing. Technical feasibility of the system as well as cost effectiveness and energy efficiency will also be discussed. Lastly, ways to improve the system further as well as new applications will be explored.

## *Conductive Sealant Testing*

The initial goal of the team was to create a sealant that dissipated enough power to generate the heat necessary to melt snow. The team's original idea was to add chemical polymers to the sealant that could possibly heat up upon contact with rain or snow and prevent snow from ever accumulating. It quickly became apparent that such a polymer did not exist in a form that would be cost efficient and effective for a homeowner, the target consumer group. The team then attempted to make conventional driveway sealant conductive by incorporating various additives.

The conductive sealant testing was unsuccessful in reducing the resistance of the sealant to target levels. The high resistance made it impossible to push sufficient current through the sealant. Part of the reason for the high resistance was the difficulty in distributing additives evenly through the sealant. Over time these sank to the bottom of the sealant, rendering it impossible to pass current. Furthermore, the quantities of additives required to allow current flow even while the additives were suspended would be far too high to justify their usage.

In a final attempt, a sheet of carbon fiber mesh was laid on the bottom of the sealant. Although this also did not provide sufficiently low resistance, it did guide the research in a more profitable direction by demonstrating that a connected conductor embedded in sealant, in this case the carbon fiber sheet, might carry sufficient current for the pavement heating application. The next step was to find what kind of embedded conductor, specifically some type of wire, would provide resistance values closer to theoretical demands at an economical cost.

### *Small Scale Testing*

Unsure of what type of metal wire to test and trying to remain cost effective, testing began using various types of readily available steel and stainless steel wires. While the resistances were close to targets, some of the wires did not transfer heat well. Thus, the literature on heating applications was analyzed to identify types of heating elements already in common use. The heating elements that defrost the back windows of cars were briefly examined before the team decided to try the main heating element in most toasters and other resistance heaters, Nichrome wire.

Initial testing of the Nichrome wire was done on 6-inch diameter asphalt pucks. Testing performed at this scale could be used to explore the thermal properties of the Nichrome wire – how it generated and dissipated heat. A practical problem the team encountered was holding the wire down flat on the puck. The wire was elastic as delivered from the factory rolled on a spool. Attempts to flatten the wire were unsuccessful. Looking back, one potentially fruitful option that was not explored was to use some sort of epoxy to hold down the wires. Ideally, this would have been a cheap way to fix the wires in place until the sealant could be applied. In the end, the final solution was to tape small loops of the steel wire to the sides of the puck as attachment points for the wire. The Nichrome wire was threaded through the loops, which kept the wire flat on the surface.

The next difficulty the team encountered was how to apply a thick layer of sealcoat over the wire. The Blackjack sealcoat used originally was too thin alone to cover the wire adequately, requiring an additive to thicken it. Sand was tried first, as it is often used in similar applications. This worked to some extent, but also caused cracking in the dried surface. Dr. Ray Bonaquist recommended adding hydrated lime, though testing showed that this would not work as desired. When added in larger quantities, the mixture became overly viscous and was unable to be spread. Furthermore, this thick layer became overly brittle upon drying, leading to potential durability issues. Since there was insufficient time to zero in on an optimum amount of hydrated lime, it was abandoned in favor of the fine sand.

Once the team was satisfied with the wiring design and sealcoat thickness for the pucks, numerous pucks were covered with the Nichrome wire for small-scale testing. The primary results from the small-scale testing came from the combination of temperature testing at both room temperature and sub-freezing temperature settings. When the puck was hooked up to the transformer at room temperature, the temperature measured on the surface of the asphalt puck increased by over $30^{o}$C in 40 minutes. This was a significant result as it meant that the heat generated from the Nichrome wire was being distributed over the surface of the puck. There was some concern whether a similar temperature increase would occur when the system was run in cold temperatures. The results from the freeze chamber testing confirmed that the system could indeed work in cold temperatures. After 35 minutes of current flow in the freeze chamber, 3 of the 4 locations exhibited a temperature rise of about $35^{o}$C. The 4th location had some strange temperature fluctuations that eventually stabilized after about 10 minutes at a $25^{o}$C increase. Despite the fluctuations, this was still a significant temperature rise. Overall, this experiment showed temperature changes measured under room temperature conditions can also be expected under sub-freezing temperatures, a vital finding for snow melting applications.

One possible explanation for the strange temperature readings at the 4th location on the puck in the freeze chamber is measurement error/variability. The thermometer used to measure temperature was a Fluke 61 infrared laser thermometer. It appeared that the thermometer did not measure the temperature at the exact location of the laser beam. Also, the angle at which the thermometer was held caused fluctuations in the temperature readings. Thus, the data from the infrared thermometer may not have always been reliable.

As a conclusion to the small-scale puck testing, ice was melted at both room temperature and below freezing in the freeze chamber. Both the room temperature and sub-freezing small scale tests demonstrated that the system did indeed have the capability of melting snow/ice as compared to a control specimen with no heating element. The melting results were better for the room temperature test, but this was most likely due to the ice sitting at room temperature and melting due to the warmer ambient conditions.

The team performed one additional small scale test to determine appropriate wire spacing for a large scale experiment. The Nichrome wire was laid on a puck in a single loop and temperatures were measured on the surface of the asphalt to determine how far the heat spread. This was vital information in determining how widely we could space wires and still melt snow, which in turn was an important factor for determining the power density for the system. A target power density from the literature review and theoretical calculations would be used to determine the sizing of the system. Having already decided that the large scale test would be the width of a parking space, the length of the test was dictated by the spacing of the wires and the number of wires required for the desired resistance. The small-scale test revealed that heat spread about an inch from the wire which dictated the wire spacing of two inches, ensuring no single point was more than an inch from a heated wire.

### *Large Scale Testing – Parking Space*

Once the total resistance for the system was determined, the PSpice analysis software was used to design the large scale circuit. The software determined that the resistance of a fully parallel circuit system was too low to get a system with any length near the length of a typical parking space and thus every fifth wire was laid as a ‘triple’, in which the length of that single wire spanned the length of three wires. This brought the system to an overall resistance closer to theoretical values.

The first construction difficulty arose from laying and securing the wire to the pavement. Initial plans were to use a staple gun to attach the wire as flush as possible against the asphalt surface. To the dismay of the team, the staple gun was not powerful enough to penetrate the asphalt. The asphalt surface was also not as smooth as expected, further complicating the laying of the wire. The solution to this was to attach the wire using masonry nails and washers. The masonry nails easily penetrated the asphalt, but required the addition of a washer to hold the wires down. This method was successful and laying down the wire became fairly routine once the construction group became familiar with the process.

The second problem was the connection of the wire to the copper wire buses running on each side of the system. The original plan was to connect them with conductive copper tape. This did not work, as the strength of the tape was insufficient to maintain the integrity of the connection. Eventually the team settled on weaving the Nichrome wire through the braided copper bus wires to ensure a connection, using the copper tape sparingly to hold the connections securely. This was a time consuming process and convinced the team that in future tests a better alternative would need to be found. For the purposes of this first large-scale test, however, the wires were indeed connected and the system could function.

The third and final construction problem involved the choice of sealant and how it would be applied. For this first large-scale test, the same Blackjack sealant was used as on the smaller scale tests in the laboratory. The purpose of driveway sealant is to provide a thin layer of protection for the underlying asphalt; it is not intended to be applied in the thicker layer that the system requires. In order to cover the entire system to the desired thickness, fine sand was added to the sealant. Even with this, multiple coats of sealant were required, and nearly two full buckets of sealant were needed to seal the parking space; a normal bucket can seal an average driveway. This large amount of sealant brings the cost effectiveness question to the forefront. A better alternative would have been to use a slurry seal, but because of time constraints this was not feasible.  Looking forward, the team hopes to try this alternative in the future.

Cracking occurred in the sealant layer; this was attributed to applying a thicker layer than the sealant was designed for and also applying the sealant in colder weather. Sealant is typically applied during warmer temperatures, but due to the testing schedule, construction of the large-scale test system began in February of 2009, a time of year that was not optimal for the sealant.

While the overall circuit was successful, the triple wires were ineffective at producing heat. The single wire strips did produce heat, however. This confirmed that it was possible to scale up the system and produce enough heat to melt snow. The system also proved less durable than anticipated, however. The complete system had only been installed about 2 weeks when it was decided to remove the bottom half of the system because so many wires were sticking up, a probable fault of the poor sealant used. It became clear that the next system would need a more durable sealant. The wire pattern would also have to be uniform throughout the circuit to make sure heat was produced uniformly.

### *Large Scale Testing – Freezer Test*

Based on the results of the large-scale scale parking space test, an improved system was designed to be tested under cold conditions. However, as it was then late summer/early fall of 2009, it was impossible to test outdoors within a timely manner, and therefore a portable test section was designed for use in a large walk-in freezer. This system was made up of two separate panels measuring 2' by 8' and 4' by 8'. The system was constructing on a frame of 2"x4" studs spaced 16" apart sheathed with ½" plywood and a top layer of Duraroc cement board. One objective of this experiment was to evaluate the appropriate spacing between the wires in the circuit. Therefore, on the smaller panel strips of Nichrome wire were laid down an inch apart connected to copper buses running down each side, while on the larger panel the wire was spaced two inches apart. After the wires were placed, 2-3 coats of sealant were applied to embed the wires. Due to the difficulties encountered attaching the Nichrome wire to the bus in the first large-scale test it was decided to solder all connections. Unfortunately, after experimenting on a few initial wires, it was discovered that conventional rosin-core solder did not adhere to the Nichrome wire. After some additional research, acid-core solder was chosen to solder the Nichrome wire. This successfully connected the wires to the buses. Another familiar construction issue was cracking of the sealant. As the first coat of sealant dried on the smaller panel cracks were noticed running perpendicular to the wires. An additional coat was added in an attempt to mask the cracks, but this proved unsuccessful. It was then realized that the cracks were forming at the spots where the wires were taped to the Duraroc substrate, so on the larger panel, taping was minimized by instead screwing down the wires. Although this significantly reduced the problem, cracks still appeared on edges of the panel or where wires broke through the surface.

Construction of the large-scale test panels was completed in the early fall of 2009. Departments on campus were contacted to locate a freeze chamber or freezer that was sufficiently large and available for use. UMD Dining Services was very helpful and offered a freezer space at the campus sporting venues that was normally used to store concessions. Photographs, video documentation, and temperature measurements of the system while in operation were collected during the testing period. The testing was successful and proved that a system could melt snow under freezing conditions.

The next step was to evaluate the snow melting system against the initial design objectives of producing an easily retrofittable system that was cost effective, energy efficient, and durable. The system was able to be retrofitted onto existing pavement, and it did not require the addition of sub-surface wires, pipes, or other heating elements. The wires were able to be laid upon a smooth surface and kept in place by the adhesive properties of asphalt sealant. The parking lot tests suggested that the system is durable, as long as the asphalt seal coat is properly maintained. The busses also need to be placed out of the way of traffic, such that repeated compression from vehicular traffic does not damage the connections.

Unfortunately, the final design was not as cost effective as intended. Construction of the system was laborious and time consuming. For example, it took approximately 12 hours to lay down the wire on each of the large scale test panels and solder them the buses. It then took additional time to apply a coat of sealant and wait for it to cure, a process which had to be repeated for 2-3 more layers. These construction times would require the pavement area to be cordoned off and out of use for at least 2-3 days. Furthermore, there are concerns over improper installation: if the wires are not secured correctly they may lift off the pavement surface; if the sealant coat is not applied thick enough cracking could occur and wires may be exposed; and the circuit must be custom designed for each application.

The initial costs for the panel test are listed in Table 9 below. Extrapolating these to the size of an entire residential driveway would mean that the cost is much too high for most Americans to afford. The average American has a driveway that is around 900 square feet, which results in a total initial installation cost for the current system of approximately $8,280. Table 10Table 10 depicts the operating cost to melt several snow depths. One can look to the snowfall during the winter of 2009-2010 to estimate an upper bound for the operating costs of the system. This season was an anomaly, with total snowfall of 55 inches, well exceeding the annual average. The system would require 660kWh to melt all the snow at a rate of 12 kW over a period of 55 hours for a 400 sq ft driveway. With the average price of electricity of Maryland being approximately 14 cents per kWh, it would cost the homeowner $92 over the entire season to melt the 55 inches of snowfall, which is an extreme amount of snow for the Mid-Atlantic region. Compare this to an average price of $75 per driveway plowing and it is clear that the system will almost always pay for its variable cost and often exceed it. Even though it appears that this operating cost is acceptable, the high start up cost might deter many potential customers from purchasing the system. However, if the materials were bought in bulk and the system mass produced, the initial construction costs would likely decrease significantly and thus the total price would be more reasonable.

**Table 9. Initial Installation Costs**

| Material | Cost for Panel Test | Unit Cost |
|---|---|---|
| Nichrome[1] | $130 for 400 ft | $0.33 per ft or $4.13 per sq ft |
| Copper Wire[2] | $25 for 100 ft | $0.25 per ft or $0.07 per sq ft |
| Transformers | $320 | N/A |
| Sealant | $50 for 48 sq ft | $1.04 per sq ft |
| Sand | $10 for 48 sq ft | $0.21 per sq ft |
| Construction Supplies and Labor | $180 for 48 sq ft | $3.75 per sq ft |
| Total | $715 | $9.20 per sq ft |

Area of Panels = 48 sq. ft

[1] Assuming 1” spacing = 12.5ft Nichrome wire per sq ft

[2] Assuming .25 ft Copper wire per sq ft

**Table 10. Operating Cost by Snow Depth**[3]

| Snow Depth | Approximate Cost |
|---|---|
| 1” | $1.38 |
| 3” | $4.14 |
| 6” | $8.28 |
| 12” | $16.56 |

[3] Assume need 30 watts/sq ft to melt 1 inch of snow per hour with a 400 sq ft driveway = 12kWh at $0.14 /kWh

## *System Improvements and Future Applications*

The high cost to install the SnowMelt system makes calls into question the feasibility of its installation on residential driveways. Despite the cost issue, one thing is still abundantly clear: the system did indeed melt snow and demonstrated proof of concept. While some of the construction costs could be mitigated through improved design, the electrical power requirement for system operation is a much bigger problem. No matter how the system is designed, in order to melt the snow on an entire driveway there is going to be a huge energy requirement that must come from the electrical grid and a current that is nearly half of the allowable current from a residential electrical service. The following paragraphs will first look at how the team can optimize some design and construction aspects of the system, and then come back to the power requirement.

The cost of the Nichrome wire is an obvious issue for the system; it has the highest cost per square foot for the initial installation. Testing showed that Nichrome wire is by far the best material to use for resistance heating, but there may still be other alternatives that might be found through research. One way to mitigate the cost issues of the Nichrome wire is to buy it in large quantities at a discount from the supplier. At commercial scale-up large amounts of Nichrome and sealant will be needed which allows for bulk purchasing, leading to decreased costs. Similarly, one more powerful but lower cost transformer would take the place of the two separate transformers. Transformers meeting these power requirements are not commercially available, necessitating custom manufacturing that was impossible in the current study due to time constraints. Even if these adjustments significantly lowered the initial construction cost of the system, it would still likely be expensive for a full-scale driveway application. This necessitates exploring other potential applications where this system could be adapted more practically.

Driveways are the most obvious choice for the SnowMelt system, but they are not the only possible use. There are other outdoor paved or surfaced areas where snowfall is equally if not more problematic than driveways but are much smaller in area. Areas such as stairs, sidewalks, and handicap parking spaces would require much lower initial cost and operating power. These areas are also ones where snow removal is particularly important. The main reason for clearing snow off driveways is for cars to get in and out, but for sidewalks and stairs the issue is people slipping and falling, potentially causing bodily harm. In a way this application of the SnowMelt system is more useful to society than it would be on driveways.

Earlier calculations showed that the total power requirement needed to melt 1 inch of snow per hour was approximately 30 watts/sq ft. For an average parking space this would mean that approximately 3 kilowatts are necessary to melt 1 inch of snow. For a sidewalk or front porch that was 3 feet wide and 50 feet long the power requirement would be 4.5 kilowatts. Both of these numbers are feasible in the sense that they are reasonable compared to the average daily household power use, 1,038 kWh per month or 35 kWh per day. By installing the system on a smaller scale, it would both appear more commercially appealing as well as reach a new group of consumers. Business owners would be more likely consumers than homeowners. This could be a more profitable target consumer-group since business owners have the fear of liability for customer injuries.

The basic design of the SnowMelt system would not change on these smaller scales. It would still be a large parallel circuit of Nichrome wires. In order to get the target resistance for each individual size of application one would have to combine series and parallel circuit elements in the same way as it was done with the two large movable test panels. The exact layout would depend on the configuration of each application, but it would be easy to design on a custom basis. One possible issue with these new applications is that it may not be able to use asphalt driveway sealant to cover the system. The most likely possible alternative would be an epoxy coating, either clear or tinted. This would be a thin plastic-like layer that would protect the system from wear and tear. In order to make sure that the epoxy layer had sufficient friction for traction, one could sprinkle sand on the surface as it dried. Durability testing would be necessary, but the concept is not far off from the driveway system.

# Chapter 5:  Conclusions

This chapter summarizes the principal conclusions from the team's three years of research. It provides a summation of the research process, focusing its analysis and critiques around the main project goals. These original goals are reviewed, and explores whether those goals were achieved or not. For goals not met, the reasons and potential future remedies are outlined.

## *Research Process Goals*

The overall objective of the research was to create an easily applicable, inexpensive, electrically conductive system using driveway sealant that could be retrofitted to existing driveways and similar types of paved surfaces. A surface installation, using a heating mechanism embedded in a layer of driveway sealant, allows the flexibility to install such a system with minimal reconstruction of the pavement. This is in contrast to existing systems, which are embedded in the concrete or asphalt during initial construction, and require removal of that surface to install later. The system would alleviate the need to use corrosive road salt on driveways.

## *Accomplishments*

### Melting Snow

The first research goal was to have a system that would melt falling and accumulating snow off of a pavement. Large scale outdoor testing during a snowstorm in the Washington, DC area conclusively demonstrated that this goal was accomplished. However, this achievement came only after many laboratory and field trials and changes to the overall research scope.

### Embedment in Sealant

Another research goal was to design a system that could be embedded into conventional driveway sealant, for ease of retrofitting to existing driveway surfaces. Using a heating grid comprised of Nichrome wire covered by a coat of sealant met this goal. The observed cracking in the sealant offers obvious room for improvement. While such cracking did not affect the heating performance of the system, it does affect the long-term durability. As the system is designed for use over multiple seasons before a reapplication of sealant is required, further development of the system would need to explore more durable alternatives. Furthermore, as the sealant proved a poor thermal conductor, an alternative material should provide better conduction of heat. Suggested improvements include using a coating material other than driveway sealant. For example, a slurry seal (mixture of fine sand in hot bitumen) would provide a thicker and more durable coating atop the wire grid. However, this alternative requires a paving contractor to install, increasing the cost to the homeowner. Similarly, other alternatives, such as epoxy coatings, have increased costs associated with them. Future research should evaluate these and other alternatives, and weigh their benefits and drawbacks in covering the resistance heating grid.

### System Construction

Efficient system construction was a goal to ensure that it could be retrofitted to existing pavement surfaces at reasonable cost. The initial large scale test revealed problems with system construction methods that were addressed and remedied in the second large scale test. The construction of the panels for the second test took a much shorter time, approximately four hours. While this is not perfectly analogous, given the scale of the panels compared to a residential installation, it does indicate that, with future improvements, this system could be installed in a reasonable amount of time. Future iterations of the system could be largely pre-fabricated, making it such that the installer need not tack down individual wires.

### Economic Analysis

Overall costs of the snow melting system were higher than expected. The initial construction cost of ~$20/sf is considerable for a small scale system. This high cost can be attributed to a number of factors. The small size of each test area, along with the steep learning curve during system design, reduced the efficiency of each installation. Given that a final design would eliminate most installation difficulties, the labor costs inherent in the construction cost would be expected to decrease. In addition, with mass production of such a system, one could take advantage of economies of scale, reducing costs in the aggregate.

The Mid Atlantic region does not experience a large amount of snowfall on average, which means that the overall costs of running the system would be in the range of about $100/year. The cost of paying a service for the snow removal of a typical driveway falls in the range of $30-50 per storm. This means that the SnowMelt system becomes economically competitive on variable costs after two snowfalls. The cost to run the system can be further reduced by using it while power is not at a peak demand, as well as through scaling back the system efficiency. Many electric companies offer variable rates based on when power is consumed. Using the system during off-peak consumption will reduce the per-kWh cost. Scaling down system efficiency would increase the melting time, but decrease the overall costs incurred. Moving forward, reductions in both installation and operation costs will be needed to make the system competitive for use by the average homeowner.

## *Overall Summary*

The SnowMelt system described in this thesis successfully melted snow from pavement surfaces in a reasonable time frame. Thorough exploration of thermal properties, power requirements, and material properties lead to the development of a low-voltage system of copper busses and Nichrome wires embedded under a layer of driveway sealant. Trial and error played a major role in enhancing this basic system concept through a series of laboratory and large scale tests.

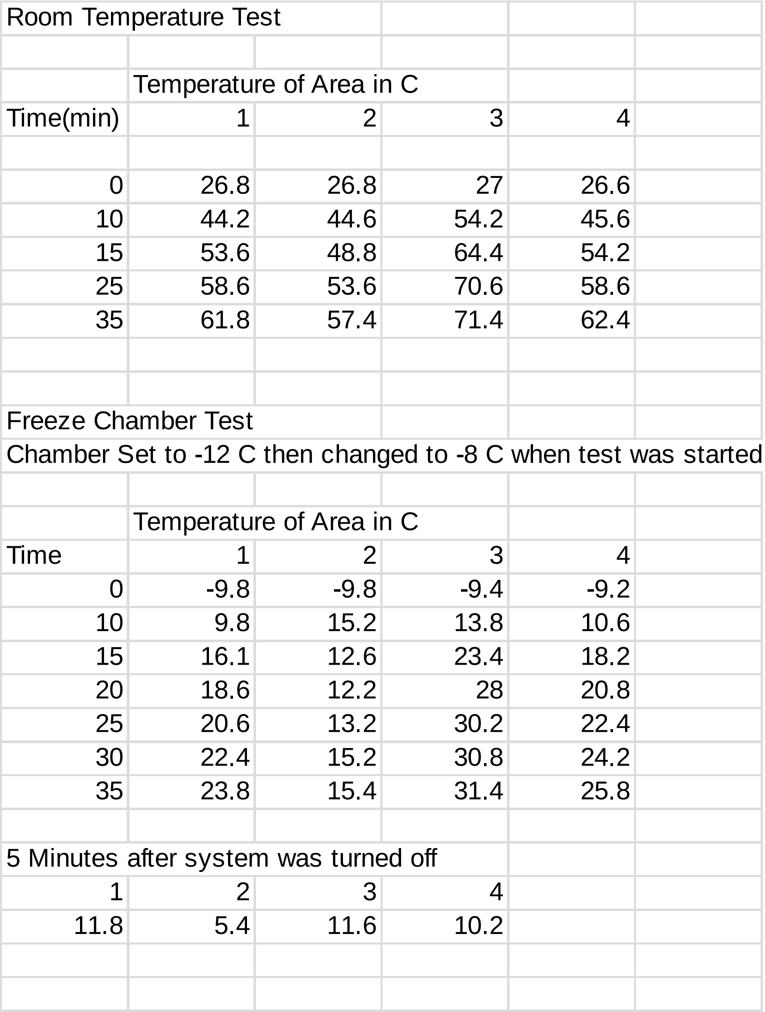
As with many engineering design projects, the process of updating and finding new and innovative ways to enhance the prototype is continuous. There are still numerous system improvements and adaptations that could be explored. Principal amongst these are:

- The development of a pre-fabricated, modular design to ease installation
- Continued refinement of resistance heating materials to lower costs
- Continued development of the sealant layer to increase thermal conductivity and increase durability
- Development of an electrical delivery system specifically suited to this application
- Determination of market potential for system in small-scale applications

# Appendix A. Additional Figures and Accrued Data

| Year | Fatalities | Injuries |
|---|---|---|
| 2000 | 41 | 182 |
| 2001 | 18 | 173 |
| 2002 | 17 | 105 |
| 2003 | 28 | 112 |
| 2004 | 28 | 190 |
| 2005 | 34 | 72 |
| 2006 | 17 | 109 |
| 2007 | 9 | 159 |
| 2008 | 21 | 121 |

**Figure A1.Snow Storm Related Injuries and Deaths (NOAA)**



Room Temperature Test

| | Temperature of Area in C | | | |
|---|---|---|---|---|
| Time(min) | 1 | 2 | 3 | 4 |
| 0 | 26.8 | 26.8 | 27 | 26.6 |
| 10 | 44.2 | 44.6 | 54.2 | 45.6 |
| 15 | 53.6 | 48.8 | 64.4 | 54.2 |
| 25 | 58.6 | 53.6 | 70.6 | 58.6 |
| 35 | 61.8 | 57.4 | 71.4 | 62.4 |

Freeze Chamber Test

Chamber Set to -12 C then changed to -8 C when test was started

| | Temperature of Area in C | | | |
|---|---|---|---|---|
| Time | 1 | 2 | 3 | 4 |
| 0 | -9.8 | -9.8 | -9.4 | -9.2 |
| 10 | 9.8 | 15.2 | 13.8 | 10.6 |
| 15 | 16.1 | 12.6 | 23.4 | 18.2 |
| 20 | 18.6 | 12.2 | 28 | 20.8 |
| 25 | 20.6 | 13.2 | 30.2 | 22.4 |
| 30 | 22.4 | 15.2 | 30.8 | 24.2 |
| 35 | 23.8 | 15.4 | 31.4 | 25.8 |

5 Minutes after system was turned off

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| 11.8 | 5.4 | 11.6 | 10.2 |

**Figure A2. Laboratory Puck Test Data**

| Time | Temperature (C) of Location on Outdoor Large Scale Test | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
| 10:00 | 23.8 | 23.8 | 26.6 | 26.6 | 29.4 | 29.4 | 30.4 | 30.4 | 30.4 | 30.4 | 28.2 | 28.2 |
| 10:30 | 24.8 | 26.2 | 27.2 | 27.6 | 31.8 | 32.2 | 34.4 | 38.2 | 33.2 | 37.8 | 32.8 | 39 |
| 11:00 | 26.8 | 29.8 | 28.8 | 28.8 | 36.6 | 36.6 | 37.2 | 41.2 | 37.2 | 42.2 | 37.4 | 42.6 |
| 11:30 | 27.6 | 29.2 | 29.2 | 29.8 | 39.6 | 41 | 43 | 47.2 | 42.2 | 47.2 | 41.8 | 47 |
| 12:00 | 28.6 | 32.4 | 29.4 | 30 | 44.4 | 45.8 | 48.2 | 52.2 | 46.4 | 48.4 | 45.6 | 52.2 |

| Time | Temperature (C) of Location on Outdoor Large Scale Test | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 7 | | Gray Shade | Gray Sun | Black Shade | Black Sun | Air Temp F | Air Temp C |
| 10:00 | 26.8 | 26.8 | | | | | | |
| 10:30 | 26.6 | 31.2 | 23 | 30 | | | 75 | 23.8888889 |
| 11:00 | 28.4 | 32.6 | 24.4 | 34.2 | 26.2 | 37 | 77 | 25 |
| 11:30 | 29 | 33.2 | 25.8 | 38.2 | 26 | 41.4 | 79 | 26.1111111 |
| 12:00 | 29.8 | 33.4 | 27 | 40.2 | 27.4 | 46.8 | 79 | 26.1111111 |

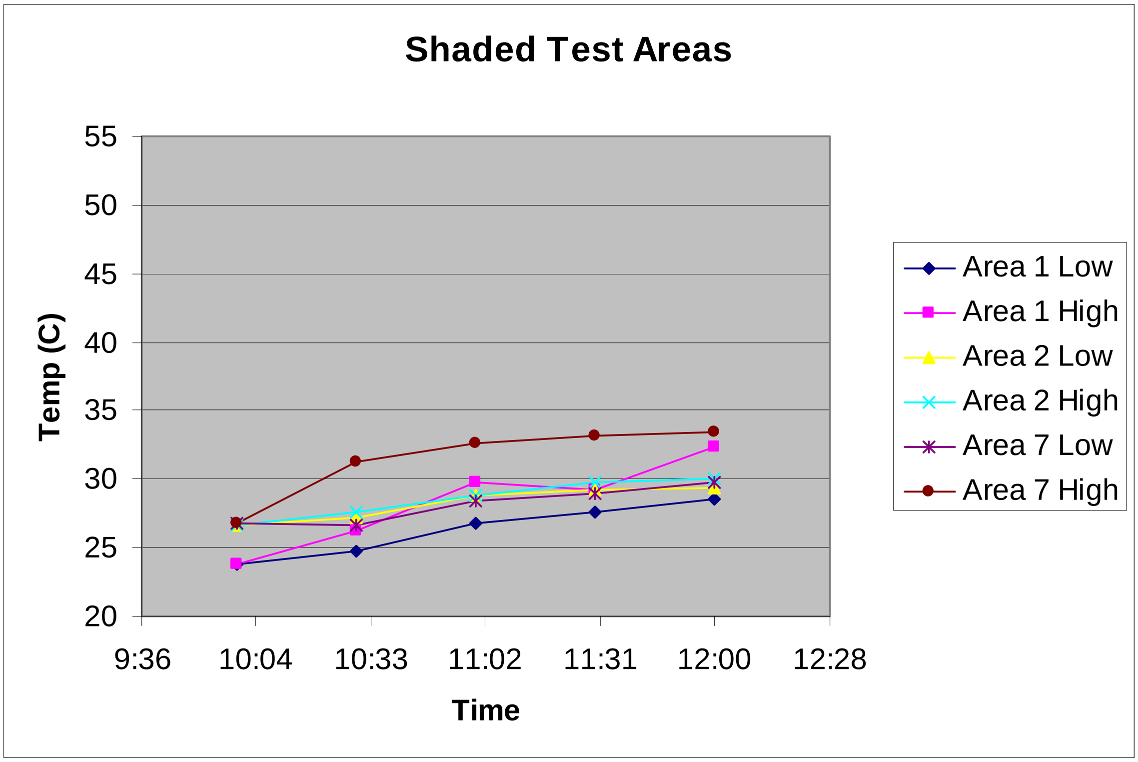
**Figure A3. Temperatures measured during test of outdoor large scale testing.**

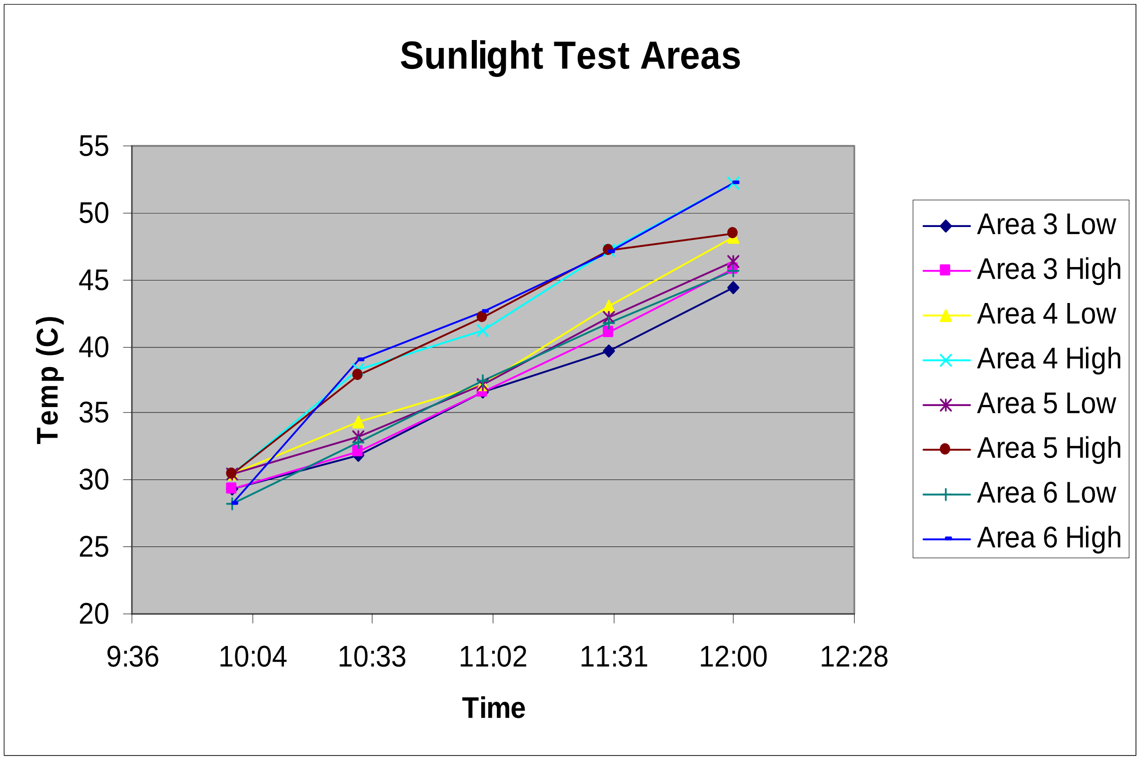
| Time | Temperature (C) of Location on Panel | | | | | |
|---|---|---|---|---|---|---|
| | A1 | A2 | A3 | A4 | A5 | A6 |
| 10:10 | -10.2 | -11.4 | -18.6 | -16 | -13.8 | -15.6 |
| 10:25 | 4 | 1.8 | -5.6 | -2.2 | 1.6 | -1.4 |
| 10:40 | 8.2 | 4.2 | -6.6 | 2 | 5 | -4.2 |
| 10:55 | 5 | 6.8 | -1 | 3.6 | 4.6 | -0.6 |

| Time | Temperature (C) of Location on Panel | | | | | |
|---|---|---|---|---|---|---|
| | B1 | B2 | B3 | B4 | B5 | B6 |
| 10:10 | -9.6 | -10.4 | -16.2 | -13.2 | -12 | -8.2 |
| 10:25 | 2 | 1.6 | -7.6 | -2.4 | -0.6 | -3.6 |
| 10:40 | 6.4 | 6 | -8.2 | -2.8 | 3.8 | 2.4 |
| 10:55 | 6.6 | 6.4 | -3.6 | 1.4 | 6.8 | 6.4 |

| Time | Freezer Temp | |
|---|---|---|
| 10:10 | 26 | -3.33333 |
| 10:25 | 24 | -4.44444 |
| 10:40 | 24 | -4.44444 |
| 10:55 | 24 | -4.44444 |

**Figure A4. Temperatures measured during freezer test of both large and small panels during initial heating.**


Shaded Test Areas
Temp (C)
55
50
45
40
35
30
25
20
9:36
10:04
10:33
11:02
11:31
12:00
12:28
Time
Area 1 Low
Area 1 High
Area 2 Low
Area 2 High
Area 7 Low
Area 7 High


Sunlight Test Areas
Temp (C)
55
50
45
40
35
30
25
20
9:36
10:04
10:33
11:02
11:31
12:00
12:28
Time
Area 3 Low
Area 3 High
Area 4 Low
Area 4 High
Area 5 Low
Area 5 High
Area 6 Low
Area 6 High

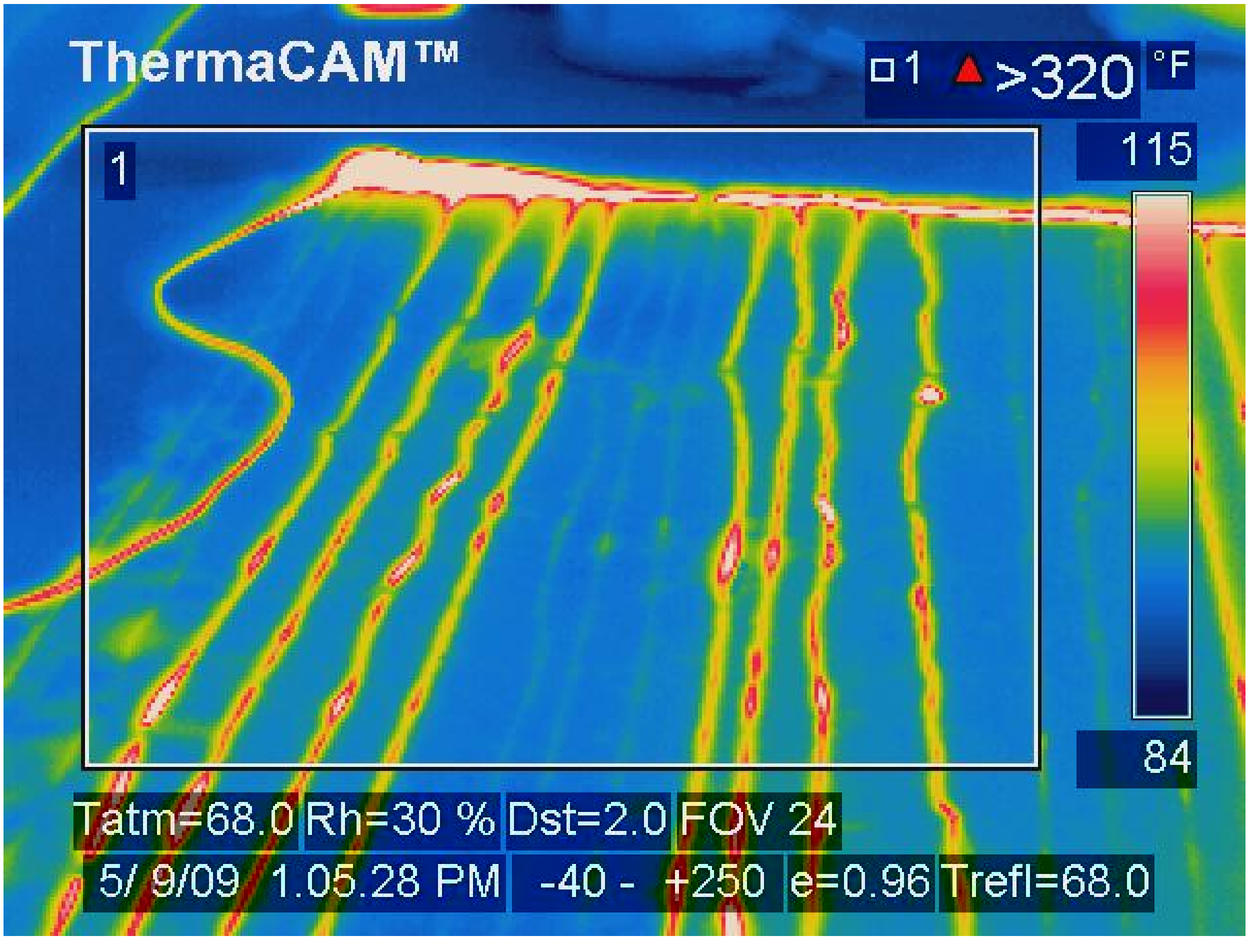


Figure A5. Additional Infrared Camera images taken during large scale outdoor testing.

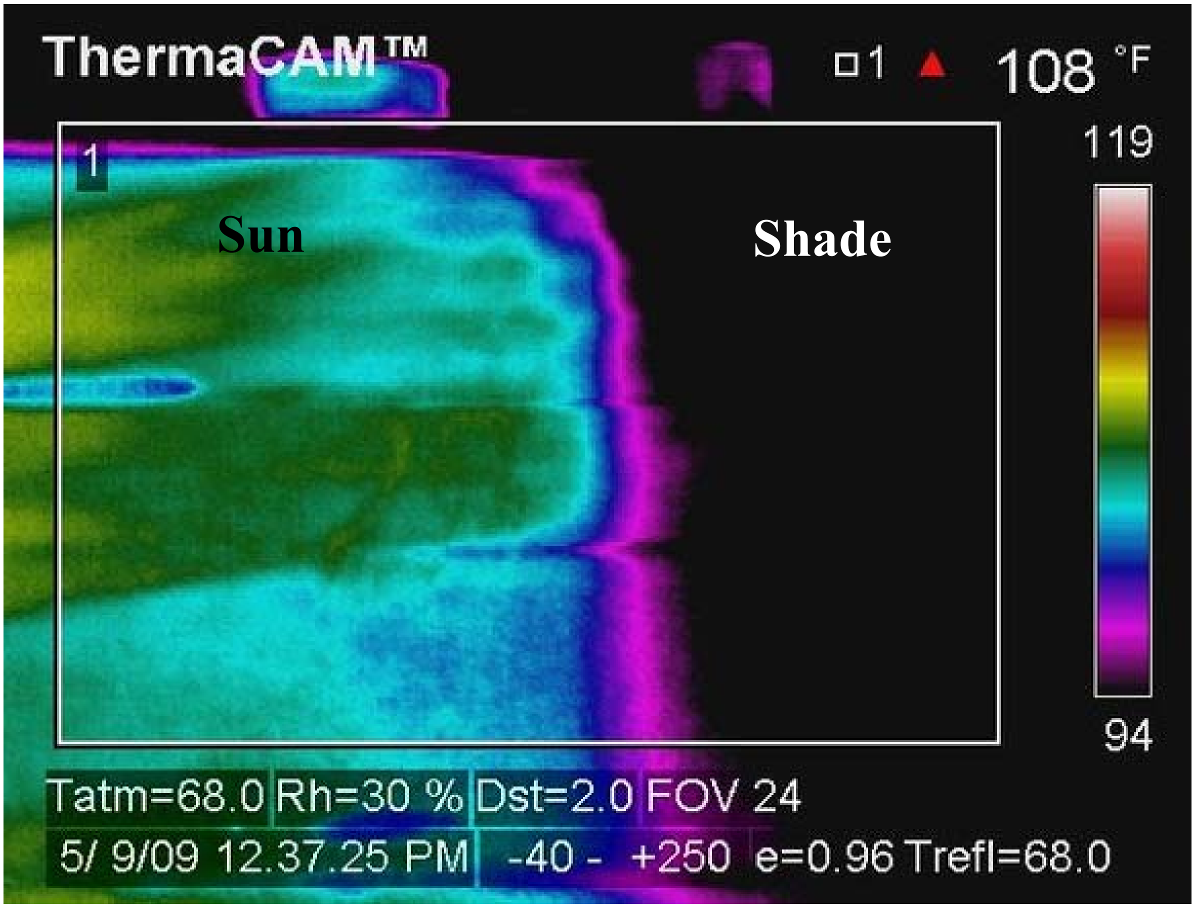


**Figure A6. Infrared Camera image of control area for large scale outdoor test. Note the marked temperature difference between areas in direct sunlight and areas in the shade of the building.**

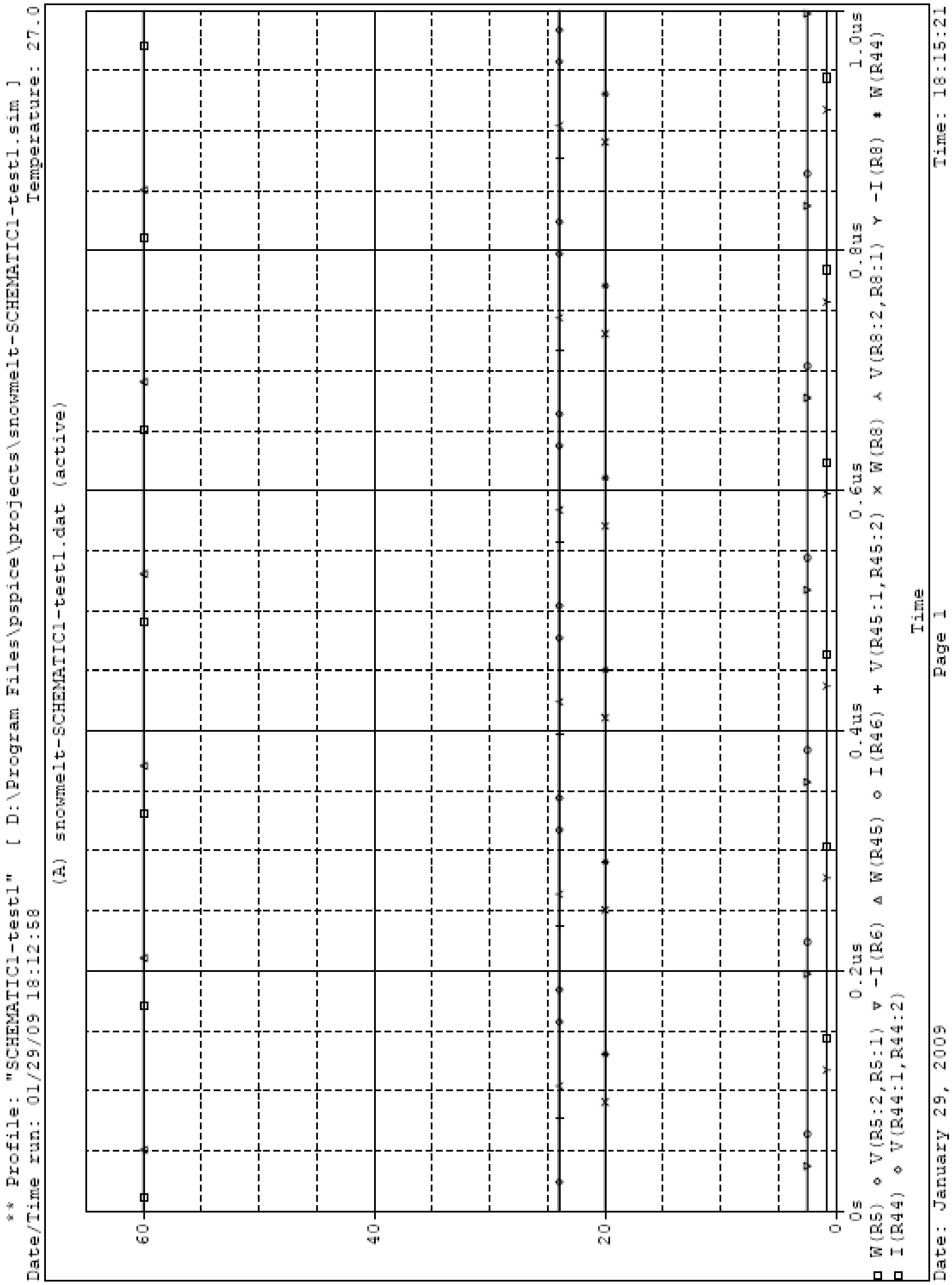
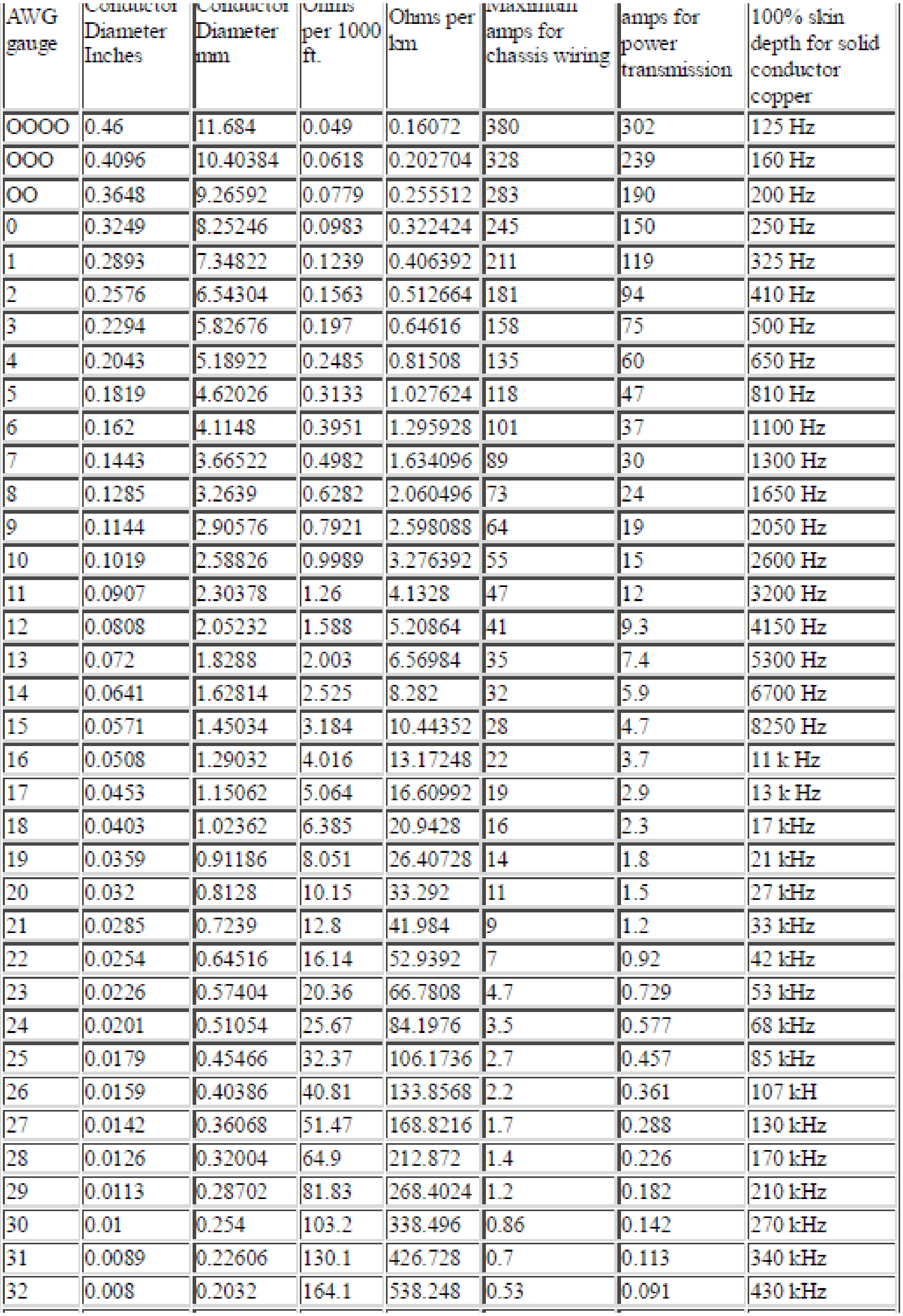


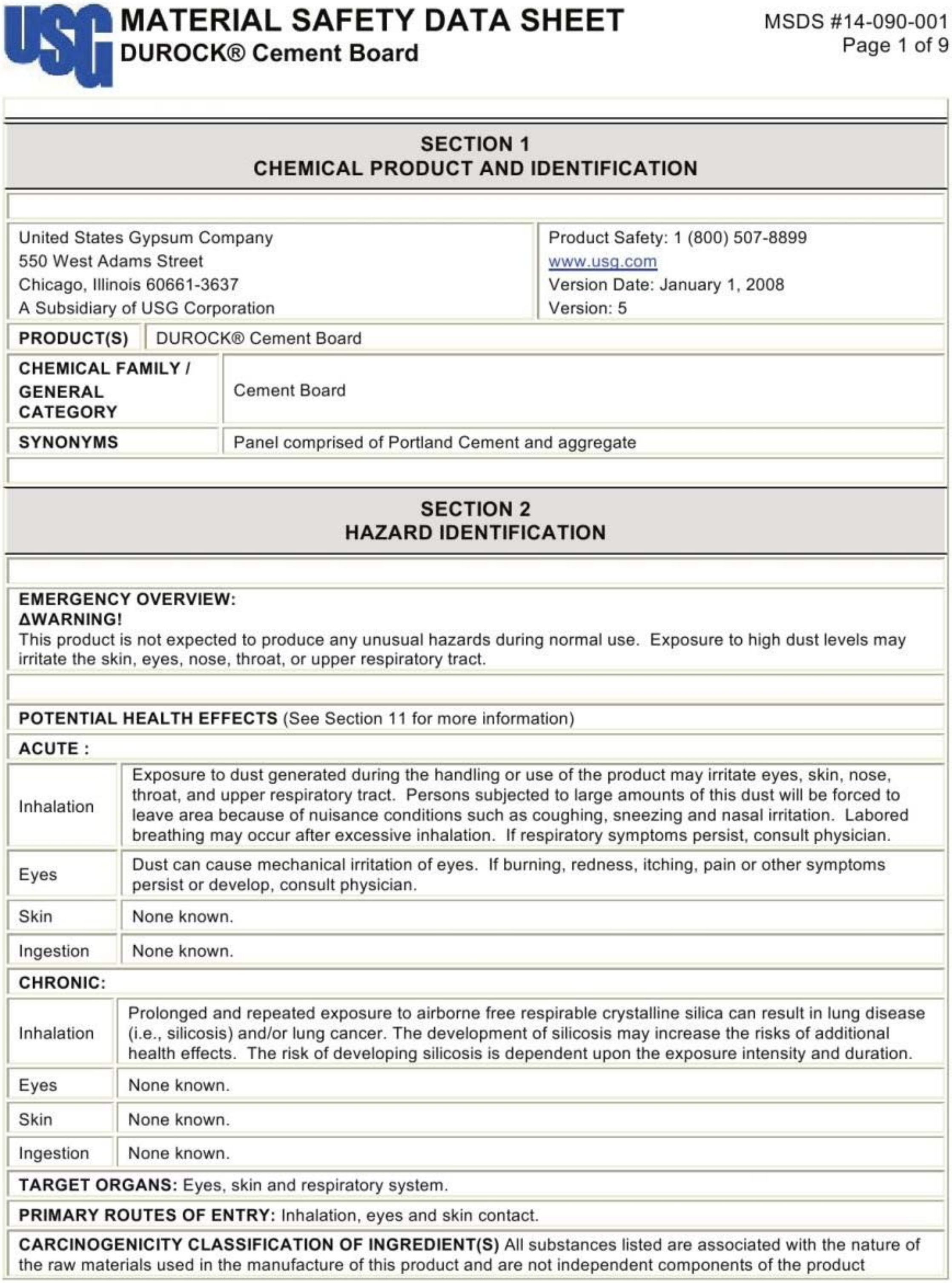
**Figure A7. PSPICE simulation results from circuit designs for the outdoor large scale test.**



| AWG gauge | Conductor Diameter Inches | Conductor Diameter mm | Ohms per 1000 ft. | Ohms per km | Maximum amps for chassis wiring | amps for power transmission | 100% skin depth for solid conductor copper |
|---|---|---|---|---|---|---|---|
| OOOO | 0.46 | 11.684 | 0.049 | 0.16072 | 380 | 302 | 125 Hz |
| OOO | 0.4096 | 10.40384 | 0.0618 | 0.202704 | 328 | 239 | 160 Hz |
| OO | 0.3648 | 9.26592 | 0.0779 | 0.255512 | 283 | 190 | 200 Hz |
| 0 | 0.3249 | 8.25246 | 0.0983 | 0.322424 | 245 | 150 | 250 Hz |
| 1 | 0.2893 | 7.34822 | 0.1239 | 0.406392 | 211 | 119 | 325 Hz |
| 2 | 0.2576 | 6.54304 | 0.1563 | 0.512664 | 181 | 94 | 410 Hz |
| 3 | 0.2294 | 5.82676 | 0.197 | 0.64616 | 158 | 75 | 500 Hz |
| 4 | 0.2043 | 5.18922 | 0.2485 | 0.81508 | 135 | 60 | 650 Hz |
| 5 | 0.1819 | 4.62026 | 0.3133 | 1.027624 | 118 | 47 | 810 Hz |
| 6 | 0.162 | 4.1148 | 0.3951 | 1.295928 | 101 | 37 | 1100 Hz |
| 7 | 0.1443 | 3.66522 | 0.4982 | 1.634096 | 89 | 30 | 1300 Hz |
| 8 | 0.1285 | 3.2639 | 0.6282 | 2.060496 | 73 | 24 | 1650 Hz |
| 9 | 0.1144 | 2.90576 | 0.7921 | 2.598088 | 64 | 19 | 2050 Hz |
| 10 | 0.1019 | 2.58826 | 0.9989 | 3.276392 | 55 | 15 | 2600 Hz |
| 11 | 0.0907 | 2.30378 | 1.26 | 4.1328 | 47 | 12 | 3200 Hz |
| 12 | 0.0808 | 2.05232 | 1.588 | 5.20864 | 41 | 9.3 | 4150 Hz |
| 13 | 0.072 | 1.8288 | 2.003 | 6.56984 | 35 | 7.4 | 5300 Hz |
| 14 | 0.0641 | 1.62814 | 2.525 | 8.282 | 32 | 5.9 | 6700 Hz |
| 15 | 0.0571 | 1.45034 | 3.184 | 10.44352 | 28 | 4.7 | 8250 Hz |
| 16 | 0.0508 | 1.29032 | 4.016 | 13.17248 | 22 | 3.7 | 11 k Hz |
| 17 | 0.0453 | 1.15062 | 5.064 | 16.60992 | 19 | 2.9 | 13 k Hz |
| 18 | 0.0403 | 1.02362 | 6.385 | 20.9428 | 16 | 2.3 | 17 kHz |
| 19 | 0.0359 | 0.91186 | 8.051 | 26.40728 | 14 | 1.8 | 21 kHz |
| 20 | 0.032 | 0.8128 | 10.15 | 33.292 | 11 | 1.5 | 27 kHz |
| 21 | 0.0285 | 0.7239 | 12.8 | 41.984 | 9 | 1.2 | 33 kHz |
| 22 | 0.0254 | 0.64516 | 16.14 | 52.9392 | 7 | 0.92 | 42 kHz |
| 23 | 0.0226 | 0.57404 | 20.36 | 66.7808 | 4.7 | 0.729 | 53 kHz |
| 24 | 0.0201 | 0.51054 | 25.67 | 84.1976 | 3.5 | 0.577 | 68 kHz |
| 25 | 0.0179 | 0.45466 | 32.37 | 106.1736 | 2.7 | 0.457 | 85 kHz |
| 26 | 0.0159 | 0.40386 | 40.81 | 133.8568 | 2.2 | 0.361 | 107 kH |
| 27 | 0.0142 | 0.36068 | 51.47 | 168.8216 | 1.7 | 0.288 | 130 kHz |
| 28 | 0.0126 | 0.32004 | 64.9 | 212.872 | 1.4 | 0.226 | 170 kHz |
| 29 | 0.0113 | 0.28702 | 81.83 | 268.4024 | 1.2 | 0.182 | 210 kHz |
| 30 | 0.01 | 0.254 | 103.2 | 338.496 | 0.86 | 0.142 | 270 kHz |
| 31 | 0.0089 | 0.22606 | 130.1 | 426.728 | 0.7 | 0.113 | 340 kHz |
| 32 | 0.008 | 0.2032 | 164.1 | 538.248 | 0.53 | 0.091 | 430 kHz |

**Figure A8. Table of American Wire Gauge Maximum ampacity for copper wire.**

# Appendix B. Datasheets from Key Materials



## MATERIAL SAFETY DATA SHEET

**DUROCK® Cement Board**

MSDS #14-090-001
Page 1 of 9

### SECTION 1
### CHEMICAL PRODUCT AND IDENTIFICATION

| | |
|---|---|
| United States Gypsum Company<br>550 West Adams Street<br>Chicago, Illinois 60661-3637<br>A Subsidiary of USG Corporation | Product Safety: 1 (800) 507-8899<br>www.usg.com<br>Version Date: January 1, 2008<br>Version: 5 |
| **PRODUCT(S)** | DUROCK® Cement Board |
| **CHEMICAL FAMILY / GENERAL CATEGORY** | Cement Board |
| **SYNONYMS** | Panel comprised of Portland Cement and aggregate |

### SECTION 2
### HAZARD IDENTIFICATION

**EMERGENCY OVERVIEW:**
**ΔWARNING!**
This product is not expected to produce any unusual hazards during normal use. Exposure to high dust levels may irritate the skin, eyes, nose, throat, or upper respiratory tract.

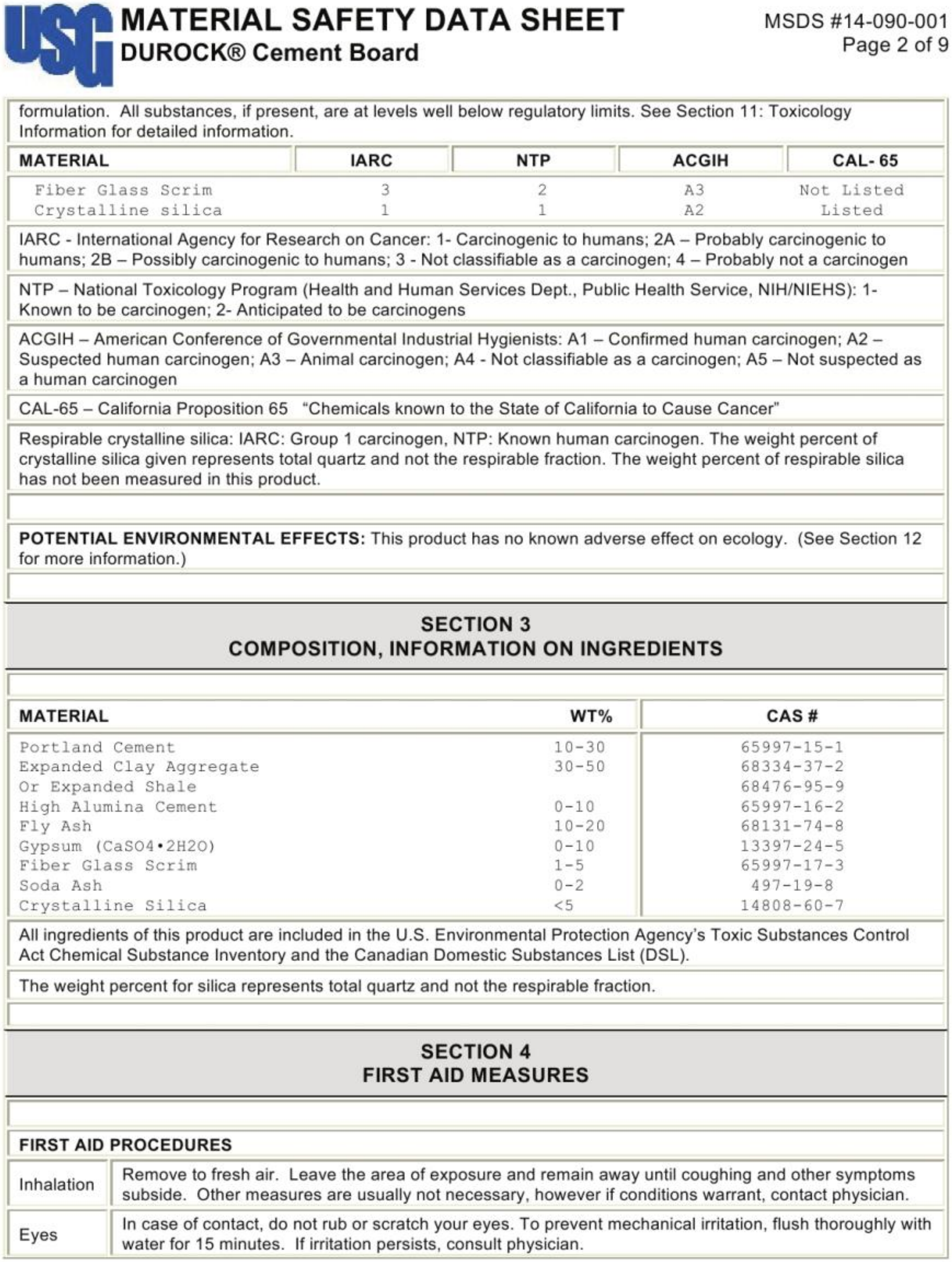
**POTENTIAL HEALTH EFFECTS** (See Section 11 for more information)

| | |
|---|---|
| **ACUTE :** | |
| Inhalation | Exposure to dust generated during the handling or use of the product may irritate eyes, skin, nose, throat, and upper respiratory tract. Persons subjected to large amounts of this dust will be forced to leave area because of nuisance conditions such as coughing, sneezing and nasal irritation. Labored breathing may occur after excessive inhalation. If respiratory symptoms persist, consult physician. |
| Eyes | Dust can cause mechanical irritation of eyes. If burning, redness, itching, pain or other symptoms persist or develop, consult physician. |
| Skin | None known. |
| Ingestion | None known. |
| **CHRONIC:** | |
| Inhalation | Prolonged and repeated exposure to airborne free respirable crystalline silica can result in lung disease (i.e., silicosis) and/or lung cancer. The development of silicosis may increase the risks of additional health effects. The risk of developing silicosis is dependent upon the exposure intensity and duration. |
| Eyes | None known. |
| Skin | None known. |
| Ingestion | None known. |

**TARGET ORGANS:** Eyes, skin and respiratory system.

**PRIMARY ROUTES OF ENTRY:** Inhalation, eyes and skin contact.

**CARCINOGENICITY CLASSIFICATION OF INGREDIENT(S)** All substances listed are associated with the nature of the raw materials used in the manufacture of this product and are not independent components of the product



**MATERIAL SAFETY DATA SHEET**
**DUROCK® Cement Board**

MSDS #14-090-001
Page 2 of 9

formulation. All substances, if present, are at levels well below regulatory limits. See Section 11: Toxicology Information for detailed information.

| MATERIAL | IARC | NTP | ACGIH | CAL- 65 |
|---|---|---|---|---|
| Fiber Glass Scrim | 3 | 2 | A3 | Not Listed |
| Crystalline silica | 1 | 1 | A2 | Listed |

IARC - International Agency for Research on Cancer: 1- Carcinogenic to humans; 2A – Probably carcinogenic to humans; 2B – Possibly carcinogenic to humans; 3 - Not classifiable as a carcinogen; 4 – Probably not a carcinogen

NTP – National Toxicology Program (Health and Human Services Dept., Public Health Service, NIH/NIEHS): 1- Known to be carcinogen; 2- Anticipated to be carcinogens

ACGIH – American Conference of Governmental Industrial Hygienists: A1 – Confirmed human carcinogen; A2 – Suspected human carcinogen; A3 – Animal carcinogen; A4 - Not classifiable as a carcinogen; A5 – Not suspected as a human carcinogen

CAL-65 – California Proposition 65 "Chemicals known to the State of California to Cause Cancer"

Respirable crystalline silica: IARC: Group 1 carcinogen, NTP: Known human carcinogen. The weight percent of crystalline silica given represents total quartz and not the respirable fraction. The weight percent of respirable silica has not been measured in this product.

**POTENTIAL ENVIRONMENTAL EFFECTS:** This product has no known adverse effect on ecology. (See Section 12 for more information.)

## SECTION 3
## COMPOSITION, INFORMATION ON INGREDIENTS

| MATERIAL | WT% | CAS # |
|---|---|---|
| Portland Cement | 10-30 | 65997-15-1 |
| Expanded Clay Aggregate | 30-50 | 68334-37-2 |
| Or Expanded Shale | | 68476-95-9 |
| High Alumina Cement | 0-10 | 65997-16-2 |
| Fly Ash | 10-20 | 68131-74-8 |
| Gypsum ($CaSO_4 \cdot 2H_2O$) | 0-10 | 13397-24-5 |
| Fiber Glass Scrim | 1-5 | 65997-17-3 |
| Soda Ash | 0-2 | 497-19-8 |
| Crystalline Silica | <5 | 14808-60-7 |

All ingredients of this product are included in the U.S. Environmental Protection Agency's Toxic Substances Control Act Chemical Substance Inventory and the Canadian Domestic Substances List (DSL).

The weight percent for silica represents total quartz and not the respirable fraction.

## SECTION 4
## FIRST AID MEASURES

**FIRST AID PROCEDURES**

| | |
|---|---|
| Inhalation | Remove to fresh air. Leave the area of exposure and remain away until coughing and other symptoms subside. Other measures are usually not necessary, however if conditions warrant, contact physician. |
| Eyes | In case of contact, do not rub or scratch your eyes. To prevent mechanical irritation, flush thoroughly with water for 15 minutes. If irritation persists, consult physician. |

| | |
|---|---|
| Skin | Wash with mild soap and water. If irritation persists, consult physician. |
| Ingestion | This product is not intended to be ingested or eaten. If gastric disturbance occurs, call physician. |

**MEDICAL CONDITIONS WHICH MAY BE AGGRAVATED:** Pre-existing upper respiratory and lung diseases such as, but not limited to, bronchitis, emphysema and asthma. Pre-existing skin diseases such as, but not limited to, rashes and dermatitis.

**NOTES TO PHYSICIAN:** Treatment should be directed at the control of symptoms and the clinical condition.

## SECTION 5
## FIRE FIGHTING MEASURES

| | |
|---|---|
| **General Fire Hazards** | None known |
| **Extinguishing Media** | Water or use extinguishing media appropriate for surrounding fire. |
| **Special Fire Fighting Procedures** | Wear appropriate personal protective equipment. See section 8. |
| **Unusual Fire/ Explosion Hazards** | None known |
| **Hazardous Combustion Products** | None known |

| | | | |
|---|---|---|---|
| **Flash Point** | Not Applicable | **Auto Ignition** | Not Applicable |
| **Method Used** | Not Applicable | **Flammability Classification** | Not Applicable |
| **Upper Flammable Limit (UFL)** | Not Determined | | |
| **Lower Flammable Limit (LFL)** | Not Determined | **Rate of Burning** | Not Applicable |

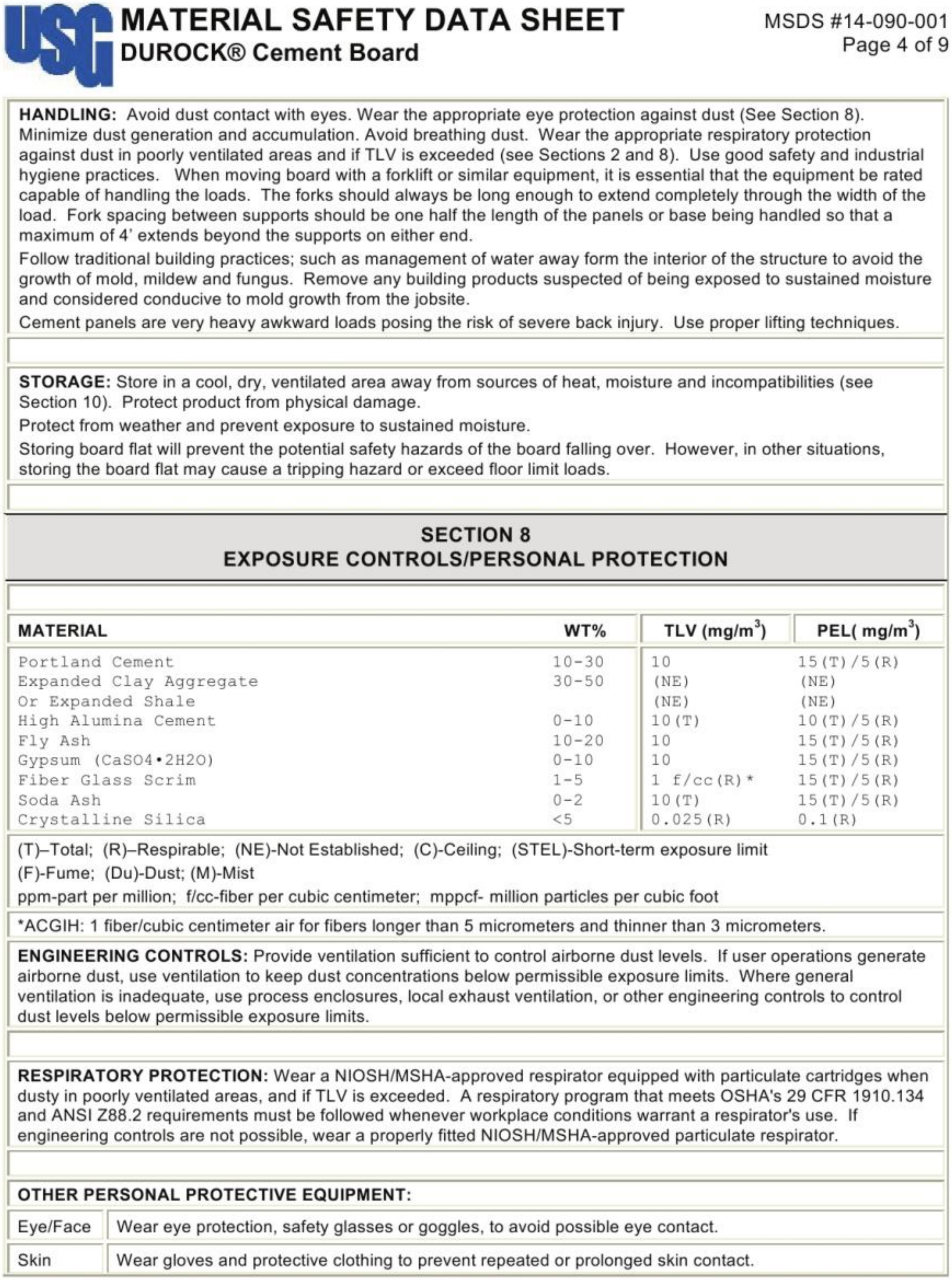
## SECTION 6
## ACCIDENTAL RELEASE MEASURES

**CONTAINMENT:** Collect panels from spillage and if not damaged or contaminated by foreign material, panels may be reclaimed.

**CLEAN-UP:** Use normal clean up procedures. No special precautions.

**DISPOSAL:** Follow all local, state, provincial and federal regulations. Never discharge large releases directly into sewers or surface waters.

## SECTION 7
## HANDLING AND STORAGE



**HANDLING:** Avoid dust contact with eyes. Wear the appropriate eye protection against dust (See Section 8). Minimize dust generation and accumulation. Avoid breathing dust. Wear the appropriate respiratory protection against dust in poorly ventilated areas and if TLV is exceeded (see Sections 2 and 8). Use good safety and industrial hygiene practices. When moving board with a forklift or similar equipment, it is essential that the equipment be rated capable of handling the loads. The forks should always be long enough to extend completely through the width of the load. Fork spacing between supports should be one half the length of the panels or base being handled so that a maximum of 4' extends beyond the supports on either end.

Follow traditional building practices; such as management of water away form the interior of the structure to avoid the growth of mold, mildew and fungus. Remove any building products suspected of being exposed to sustained moisture and considered conducive to mold growth from the jobsite.

Cement panels are very heavy awkward loads posing the risk of severe back injury. Use proper lifting techniques.

**STORAGE:** Store in a cool, dry, ventilated area away from sources of heat, moisture and incompatibilities (see Section 10). Protect product from physical damage.

Protect from weather and prevent exposure to sustained moisture.

Storing board flat will prevent the potential safety hazards of the board falling over. However, in other situations, storing the board flat may cause a tripping hazard or exceed floor limit loads.

## SECTION 8
## EXPOSURE CONTROLS/PERSONAL PROTECTION

| MATERIAL | WT% | TLV (mg/m$^3$) | PEL( mg/m$^3$) |
|---|---|---|---|
| Portland Cement | 10-30 | 10 | 15(T)/5(R) |
| Expanded Clay Aggregate | 30-50 | (NE) | (NE) |
| Or Expanded Shale | | (NE) | (NE) |
| High Alumina Cement | 0-10 | 10(T) | 10(T)/5(R) |
| Fly Ash | 10-20 | 10 | 15(T)/5(R) |
| Gypsum (CaSO4•2H2O) | 0-10 | 10 | 15(T)/5(R) |
| Fiber Glass Scrim | 1-5 | 1 f/cc(R)* | 15(T)/5(R) |
| Soda Ash | 0-2 | 10(T) | 15(T)/5(R) |
| Crystalline Silica | <5 | 0.025(R) | 0.1(R) |

(T)–Total; (R)–Respirable; (NE)-Not Established; (C)-Ceiling; (STEL)-Short-term exposure limit

(F)-Fume; (Du)-Dust; (M)-Mist

ppm-part per million; f/cc-fiber per cubic centimeter; mppcf- million particles per cubic foot

*ACGIH: 1 fiber/cubic centimeter air for fibers longer than 5 micrometers and thinner than 3 micrometers.

**ENGINEERING CONTROLS:** Provide ventilation sufficient to control airborne dust levels. If user operations generate airborne dust, use ventilation to keep dust concentrations below permissible exposure limits. Where general ventilation is inadequate, use process enclosures, local exhaust ventilation, or other engineering controls to control dust levels below permissible exposure limits.

**RESPIRATORY PROTECTION:** Wear a NIOSH/MSHA-approved respirator equipped with particulate cartridges when dusty in poorly ventilated areas, and if TLV is exceeded. A respiratory program that meets OSHA's 29 CFR 1910.134 and ANSI Z88.2 requirements must be followed whenever workplace conditions warrant a respirator's use. If engineering controls are not possible, wear a properly fitted NIOSH/MSHA-approved particulate respirator.

**OTHER PERSONAL PROTECTIVE EQUIPMENT:**

| | |
|---|---|
| Eye/Face | Wear eye protection, safety glasses or goggles, to avoid possible eye contact. |
| Skin | Wear gloves and protective clothing to prevent repeated or prolonged skin contact. |

| | |
|---|---|
| General | Selection of Personal Protective Equipment will depend on environmental working conditions and operations. |

## SECTION 9
## PHYSICAL AND CHEMICAL PROPERTIES

| | | | |
|---|---|---|---|
| **Appearance** | Gray | **Vapor Density (Air = 1)** | Not Applicable |
| **Odor** | Low to no odor | **Specific Gravity ($H_2O$ = 1)** | 1.2 |
| **Odor Threshold** | Not Determined | **Solubility in water (g/100g)** | Not Determined |
| **Physical State** | Solid (board) | **Partition Coefficient** | Not Applicable |
| **pH @ 25 ° C** | ~12 | **Auto-ignition Temp** | Not Determined |
| **Melting Point** | Not Applicable | **Decomposition Temp** | Not Determined |
| **Freezing Point** | Not Applicable | **Viscosity** | Not Applicable |
| **Boiling Point** | Not Applicable | **Particle Size** | Varies |
| **Flash Point** | Not Applicable | **Bulk Density** | ~ 2-3 lb/ft2 / 9-15 kg/m2 |
| **Evaporation Rate (BuAc = 1)** | Not Applicable | **Molecular Weight** | Mixture |
| **Upper Flammable Limit (UFL)** | Not Determined | **VOC Content** | Zero |
| **Lower Flammable Limit (LFL)** | Not Determined | **Percent Volatile** | Zero |
| **Vapor Pressure (mm Hg)** | Not Applicable | | |

## SECTION 10
## CHEMICAL STABILITY AND REACTIVITY

| | |
|---|---|
| **STABILITY** | Stable. |
| **CONDITIONS TO AVOID** | Contact with incompatibles (see below). |
| **INCOMPATIBILITY** | None known. |
| **HAZARDOUS POLYMERIZATION** | None known. |
| **HAZARDOUS DECOMPOSITION** | None known. |

## SECTION 11
## TOXICOLOGICAL INFORMATION

**ACUTE EFFECTS:** None known.

**CHRONIC EFFECTS / CARCINOGENICITY:**

Crystalline Silica: Exposures to respirable crystalline silica are not expected during the normal use of this product; however, actual levels must be determined by workplace hygiene testing. The weight percent of respirable crystalline silica may not have been measured in this product. Prolonged and repeated exposure to airborne free respirable crystalline silica can result in lung disease (i.e., silicosis) and/or lung cancer. The development of silicosis may increase the risks of additional health effects. The risk of developing silicosis is dependent upon the exposure intensity and duration.

In June, 1997, IARC classified crystalline silica (quartz and cristobalite) as a human carcinogen. In making the overall evaluation, the IARC Working Group noted that carcinogenicity in humans was not detected in all industrial circumstances studied. Carcinogenicity may be dependent on inherent characteristics of the crystalline silica or on external factors affecting its biological activity or distribution of its polymorphs.

IARC states that crystalline silica inhaled in the form of quartz or cristobalite from occupational sources is carcinogenic to humans (Group 1).

## SECTION 12
## ECOLOGICAL INFORMATION

**ENVIRONMENTAL TOXICITY:** This product has no known adverse effect on ecology.

| | |
|---|---|
| **Ecotoxicity value** | Not determined. |

## SECTION 13
## DISPOSAL CONSIDERATIONS

**WASTE DISPOSAL METHOD:** Dispose of material in accordance with federal, state, and local regulations. Never discharge directly into sewers or surface waters. Consult with environmental regulatory agencies for guidance on acceptable disposal practices.

## SECTION 14
## TRANSPORT INFORMATION

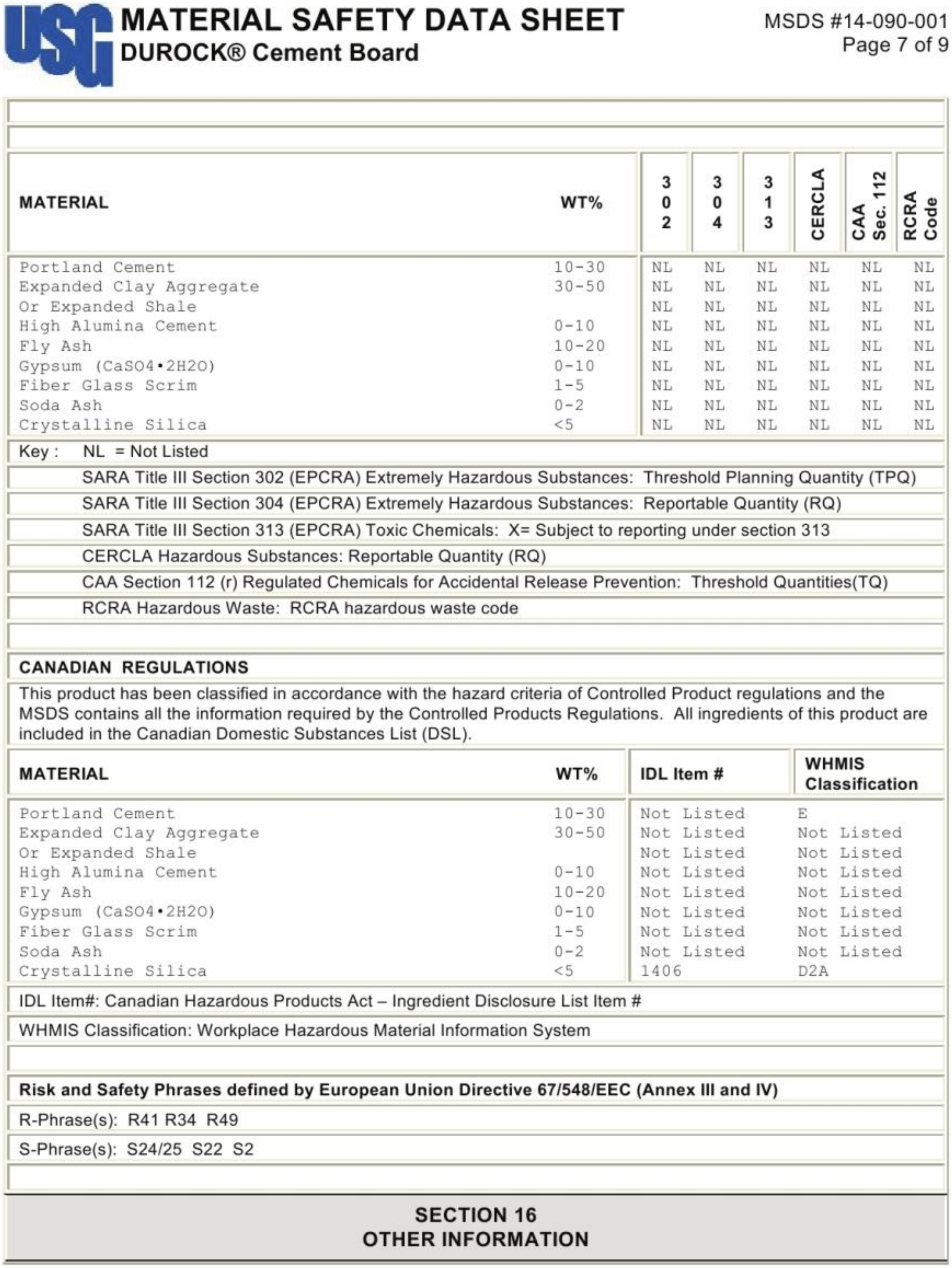
**U.S. DOT INFORMATION:** Not a hazardous material per DOT shipping requirements. Not classified or regulated.

| | |
|---|---|
| **Shipping Name** | Same as product name. |
| **Hazard Class** | Not classified. |
| **UN/NA #** | None. Not classified. |
| **Packing Group** | None. |
| **Label (s) Required** | Not applicable. |
| **GGVSec/MDG-Code** | Not classified. |
| **ICAO/IATA-DGR** | Not applicable. |
| **RID/ADR** | None. |
| **ADNR** | None. |

## SECTION 15
## REGULATORY INFORMATION

**UNITED STATES REGULATIONS**

All ingredients of this product are included in the U.S. Environmental Protection Agency's Toxic Substances Control Act Chemical Substance Inventory.



| MATERIAL | WT% | 302 | 304 | 313 | CERCLA | CAA Sec. 112 | RCRA Code |
|---|---|---|---|---|---|---|---|
| Portland Cement | 10-30 | NL | NL | NL | NL | NL | NL |
| Expanded Clay Aggregate | 30-50 | NL | NL | NL | NL | NL | NL |
| Or Expanded Shale | | NL | NL | NL | NL | NL | NL |
| High Alumina Cement | 0-10 | NL | NL | NL | NL | NL | NL |
| Fly Ash | 10-20 | NL | NL | NL | NL | NL | NL |
| Gypsum ($CaSO_4 \cdot 2H_2O$) | 0-10 | NL | NL | NL | NL | NL | NL |
| Fiber Glass Scrim | 1-5 | NL | NL | NL | NL | NL | NL |
| Soda Ash | 0-2 | NL | NL | NL | NL | NL | NL |
| Crystalline Silica | <5 | NL | NL | NL | NL | NL | NL |

Key : NL = Not Listed

SARA Title III Section 302 (EPCRA) Extremely Hazardous Substances: Threshold Planning Quantity (TPQ)

SARA Title III Section 304 (EPCRA) Extremely Hazardous Substances: Reportable Quantity (RQ)

SARA Title III Section 313 (EPCRA) Toxic Chemicals: X= Subject to reporting under section 313

CERCLA Hazardous Substances: Reportable Quantity (RQ)

CAA Section 112 (r) Regulated Chemicals for Accidental Release Prevention: Threshold Quantities(TQ)

RCRA Hazardous Waste: RCRA hazardous waste code

## CANADIAN REGULATIONS

This product has been classified in accordance with the hazard criteria of Controlled Product regulations and the MSDS contains all the information required by the Controlled Products Regulations. All ingredients of this product are included in the Canadian Domestic Substances List (DSL).

| MATERIAL | WT% | IDL Item # | WHMIS Classification |
|---|---|---|---|
| Portland Cement | 10-30 | Not Listed | E |
| Expanded Clay Aggregate | 30-50 | Not Listed | Not Listed |
| Or Expanded Shale | | Not Listed | Not Listed |
| High Alumina Cement | 0-10 | Not Listed | Not Listed |
| Fly Ash | 10-20 | Not Listed | Not Listed |
| Gypsum ($CaSO_4 \cdot 2H_2O$) | 0-10 | Not Listed | Not Listed |
| Fiber Glass Scrim | 1-5 | Not Listed | Not Listed |
| Soda Ash | 0-2 | Not Listed | Not Listed |
| Crystalline Silica | <5 | 1406 | D2A |

IDL Item#: Canadian Hazardous Products Act – Ingredient Disclosure List Item #

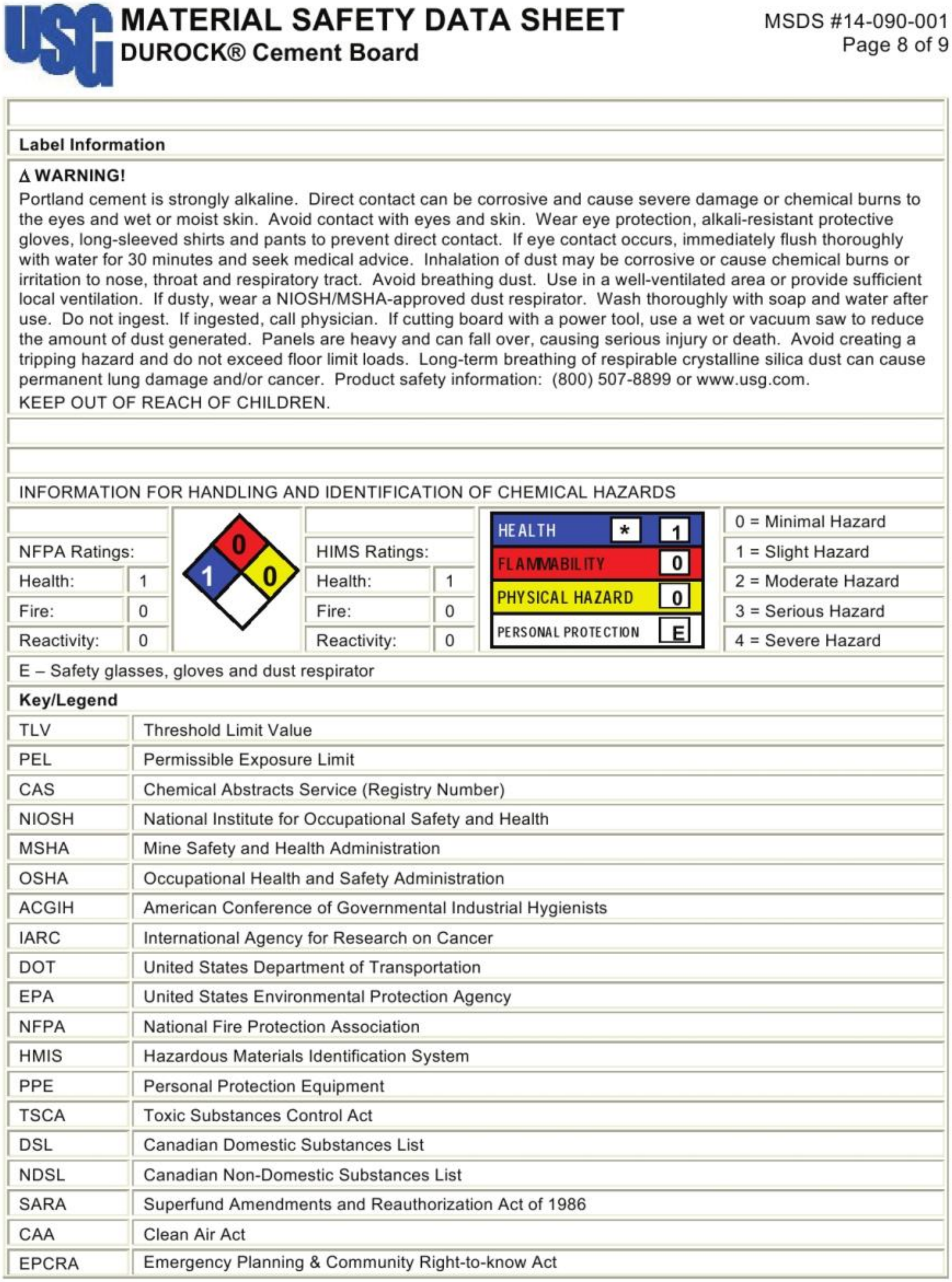
WHMIS Classification: Workplace Hazardous Material Information System

**Risk and Safety Phrases defined by European Union Directive 67/548/EEC (Annex III and IV)**

R-Phrase(s): R41 R34 R49

S-Phrase(s): S24/25 S22 S2

## SECTION 16
## OTHER INFORMATION



**Label Information**

**Δ WARNING!**

Portland cement is strongly alkaline. Direct contact can be corrosive and cause severe damage or chemical burns to the eyes and wet or moist skin. Avoid contact with eyes and skin. Wear eye protection, alkali-resistant protective gloves, long-sleeved shirts and pants to prevent direct contact. If eye contact occurs, immediately flush thoroughly with water for 30 minutes and seek medical advice. Inhalation of dust may be corrosive or cause chemical burns or irritation to nose, throat and respiratory tract. Avoid breathing dust. Use in a well-ventilated area or provide sufficient local ventilation. If dusty, wear a NIOSH/MSHA-approved dust respirator. Wash thoroughly with soap and water after use. Do not ingest. If ingested, call physician. If cutting board with a power tool, use a wet or vacuum saw to reduce the amount of dust generated. Panels are heavy and can fall over, causing serious injury or death. Avoid creating a tripping hazard and do not exceed floor limit loads. Long-term breathing of respirable crystalline silica dust can cause permanent lung damage and/or cancer. Product safety information: (800) 507-8899 or www.usg.com.

KEEP OUT OF REACH OF CHILDREN.

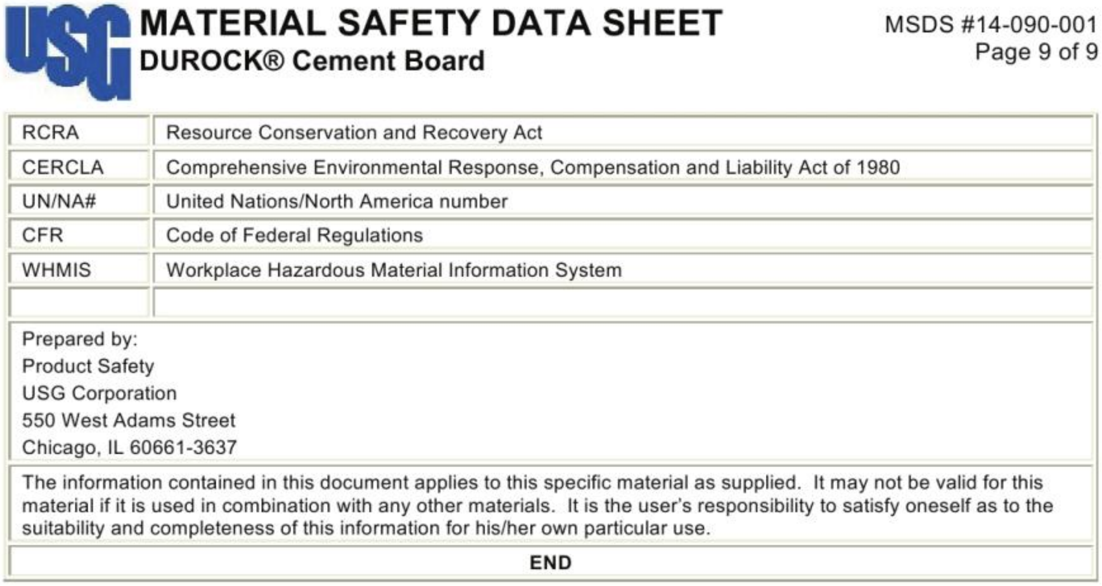
INFORMATION FOR HANDLING AND IDENTIFICATION OF CHEMICAL HAZARDS

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | HEALTH | * 1 | 0 = Minimal Hazard |
| NFPA Ratings: | | HIMS Ratings: | | FLAMMABILITY | 0 | 1 = Slight Hazard |
| Health: | 1 | Health: | 1 | PHYSICAL HAZARD | 0 | 2 = Moderate Hazard |
| Fire: | 0 | Fire: | 0 | PERSONAL PROTECTION | E | 3 = Serious Hazard |
| Reactivity: | 0 | Reactivity: | 0 | | | 4 = Severe Hazard |

E – Safety glasses, gloves and dust respirator

**Key/Legend**

| | |
|---|---|
| TLV | Threshold Limit Value |
| PEL | Permissible Exposure Limit |
| CAS | Chemical Abstracts Service (Registry Number) |
| NIOSH | National Institute for Occupational Safety and Health |
| MSHA | Mine Safety and Health Administration |
| OSHA | Occupational Health and Safety Administration |
| ACGIH | American Conference of Governmental Industrial Hygienists |
| IARC | International Agency for Research on Cancer |
| DOT | United States Department of Transportation |
| EPA | United States Environmental Protection Agency |
| NFPA | National Fire Protection Association |
| HMIS | Hazardous Materials Identification System |
| PPE | Personal Protection Equipment |
| TSCA | Toxic Substances Control Act |
| DSL | Canadian Domestic Substances List |
| NDSL | Canadian Non-Domestic Substances List |
| SARA | Superfund Amendments and Reauthorization Act of 1986 |
| CAA | Clean Air Act |
| EPCRA | Emergency Planning & Community Right-to-know Act |



| | |
|---|---|
| RCRA | Resource Conservation and Recovery Act |
| CERCLA | Comprehensive Environmental Response, Compensation and Liability Act of 1980 |
| UN/NA# | United Nations/North America number |
| CFR | Code of Federal Regulations |
| WHMIS | Workplace Hazardous Material Information System |
| | |

Prepared by:
Product Safety
USG Corporation
550 West Adams Street
Chicago, IL 60661-3637

The information contained in this document applies to this specific material as supplied. It may not be valid for this material if it is used in combination with any other materials. It is the user's responsibility to satisfy oneself as to the suitability and completeness of this information for his/her own particular use.

**END**

# Resistance Heating Wire

## Nickel-Chromium Alloy

## 60% Nickel / 16% Chromium (Balance Iron)

Shown larger than actual size.

- ✓ Used to Make Straight or Helical Coil Resistance Heaters
- ✓ Quick Heating, Long Life
- ✓ High Temperature, 1000°C (1850°F)
- ✓ Corrosion Resistant
- ✓ Convenient 15 m (50') and 60 m (200') Spools

MADE IN USA

Nickel-Chrome 60 is the world's standard of comparison in the electrical trade for metallic resistance wire. It is an alloy of 60% nickel and 16% chromium, and is the accepted material for heating devices operating up to 1000°C (1850°F). This encompasses most pluggable power cord domestic heating appliances and those heating units of medium temperatures which do not require the unsurpassed quality of NI/CR-80/20, the 80-20 alloy.

In addition to being commonly used in electrical heating, Nickel-Chrome 60 is used extensively in industrial applications for rheostats and resistance units. It makes for compact units capable of withstanding severe overloads and short circuits without damage or circuit impairment.

The excellent corrosion resistance of Nickel-Chrome 60 makes it very useful for purposes other than electrical heating. Acid dipping baskets, cyanide hardening and pickling containers, filter cloth, wire mesh, bolts and nuts are a few representative uses.

### Specifications

**Composition:** 60% Ni, 16% Cr, balance Fe

**Specific Resistance:** 675 Ω per circular mil-foot at 68°F (20°C); see table below for multiplication factors to obtain resistance at other temperatures

**Specific Gravity:** 8.25

**Density:** 0.298 lb/in$^3$

**Melting Point:** Approx 1350°C (2450°F)

**Nominal Coefficient of Linear Expansion:**
0.000017 (20 to 1000°C)

**Tensile Strength (lb/in$^2$) at 20°C (68°F):**
**Soft Annealed:** 95,000

**Nominal Temperature Coefficient of Resistance:**
0.00015 Ω/Ω/°C (20 to 500°C)

**Factor by Which Resistance at Room Temperature Is to Be Multiplied to Obtain Resistance at Indicated Temperatures**
*(These figures are given as a basis for engineering calculations and represent average material as supplied.)*

| **Temp °C** | 20 | 93 | 204 | 315 | 427 | 538 | 649 | 760 | 871°C |
|---|---|---|---|---|---|---|---|---|---|
| **Temp °F** | 68 | 200 | 400 | 600 | 800 | 1000 | 1200 | 1400 | 1600°F |
| **Factor** | 1.000 | 1.019 | 1.044 | 1.070 | 1.092 | 1.108 | 1.112 | 1.118 | 1.13 |

▨ ***MOST POPULAR MODELS HIGHLIGHTED!***

**To Order** *(Specify Model Number)*

| AWG | Dia. mm (in) | Ω per ft @ 20°C (68°F) | Current Temperature Characteristics* °C (°F) | | | | | | Model No. | Price | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 425 (800) | 550 (1000) | 650 (1200) | 750 (1400) | 875 (1600) | 1100 (2000) | | 15 m (50') | 60 m (200') |
| 18 | 1.0 (0.040) | 0.4219 | 7.90 | 9.75 | 11.96 | 14.51 | 17.37 | 23.08 | **NI60-040-(†)** | **$21** | **$63** |
| 20 | 0.81 (0.032) | 0.6592 | 5.92 | 7.25 | 8.86 | 10.69 | 12.72 | 16.87 | **NI60-032-(†)** | **16** | **48** |
| 22 | 0.64 (0.0253) | 1.055 | 4.44 | 5.40 | 6.56 | 7.87 | 11.63 | 12.33 | **NI60-025-(†)** | **16** | **48** |
| 24 | 0.51 (0.0201) | 1.671 | 3.32 | 4.01 | 4.86 | 5.80 | 6.82 | 9.01 | **NI60-020-(†)** | **16** | **48** |
| 26 | 0.40 (0.0159) | 2.670 | 2.52 | 3.00 | 3.61 | 4.31 | 5.06 | 6.63 | **NI60-015-(†)** | **10** | **30** |
| 28 | 0.32 (0.0126) | 4.252 | 1.90 | 2.28 | 2.73 | 3.23 | 3.77 | 4.88 | **NI60-012-(†)** | **10** | **30** |
| 30 | 0.25 (0.010) | 6.750 | 1.43 | 1.74 | 2.06 | 2.43 | 2.81 | 3.59 | **NI60-010-(†)** | **10** | **30** |

** Showing approximate amperes necessary to produce a given temperature, applying only to a straight wire stretched horizontally in free air.*
*† Specify desired length in feet: **50 or 200**. **Note:** This wire is **not** intended for use in making thermocouple elements.*
***Ordering Example:** NI60-010-200 is a 200' spool of 30 gage bare 60% nickel/16% chromium alloy heating wire, **$30**.*

**Note:** Published prices are based on market value at time of printing and are subject to change due to Nickel surcharges, Chromium and precious-metal market fluctuations.

**SealMaster**
**Pavement Products & Equipment**

# Polymer Modified MasterSeal (PMM)

SMT - 106 Revised: 1/09

## 1. PRODUCT NAME

Polymer Modified MasterSeal (PMM)

## 2. MANUFACTURER

SealMaster has a nationwide network of manufacturing and distribution facilities.

Phone: 800-395-7325
www.sealmaster.net

## 3. PRODUCT DESCRIPTION & BENEFITS

Polymer Modified MasterSeal (PMM) is a high performance mineral reinforced asphalt emulsion blended with polymers and special surfactants for superior adhesion, flexibility, and durability. PMM is job-mixed with specifically graded aggregate and applied at a rate of 58-62% solids (unlike conventional sealers that are applied at 40-43% solids). The aggregate provides a safe, skid-resistant surface for both pedestrian and vehicle traffic. PMM dries faster than conventional pavement sealers that are diluted with water prior to application. PMM protects pavement from oxidation, moisture intrusion, and oil. PMM's deep, rich black color gives old, oxidized pavement a "like new" surface that melts snow and ice faster and reduces cleaning and maintenance costs.

Basic Uses: Polymer Modified MasterSeal is designed to beautify and protect asphalt pavement surfaces including parking lots, roadways, and driveways.

Composition: PMM is a polymer modified asphalt emulsion pavement sealer fortified with specialty surfactants to promote superior adhesion and durability.

Sizes: PMM is available in 4,000 gallon bulk tankers, 55-gallon drums, and 5-gallon pails.

Color: PMM dries to a deep, rich black color.

Limitations: PMM shall not be applied when temperature is expected to drop below 50°F at any time within a 24 hour period after application.

## 4. TECHNICAL DATA

ASTM Test Methods:

- D-140 Sampling of Bituminous Materials
- D-466 Methods of Testing Film Deposits from Bituminous Emulsions
- B-117 Salt Spray (FOG) Testing
- D-529 Recommended Practice for Accelerated Weathering Test Of Bituminous Materials
- D-2939 Bituminous-Base Emulsions for use as Protective Coatings

Environmental Considerations: PMM does not contain asbestos. PMM is an environmentally friendly water based pavement sealer containing less than 100 grams per liter volatile organic content (VOC).

Physical/Chemical Properties: PMM is a polymer modified asphalt emulsion fortified with special surfactants.

## 5. INSTALLATION

Surface must be clean and free from all loose material and dirt. Pavement surface repairs should be made with a suitable hot or cold asphalt mix. Cracks should be filled with SealMaster hot pour or cold applied crack fillers. Treat all grease, oil, and gasoline spots or stains with SealMaster Petro Seal or Prep Seal.

Methods: PMM shall be applied by either pressurized spray application equipment or self-propelled squeegee equipment. Pressurized spray equipment shall be capable of spraying pavement sealer with sand added. Equipment shall have continuous agitation or mixing capabilities to maintain homogeneous consistency of pavement sealer mixture throughout the application process. Self-propelled squeegee equipment shall have at least 2 squeegee or brush devices (one behind the other) to assure adequate distribution and penetration of sealer into bituminous pavement. Hand squeegees and brushes shall be acceptable in areas where practicality prohibits the use of mechanized equipment.

| TEST | SPECIFICATIONS | RESULT |
|---|---|---|
| Material | Material shall be homogenous and show no separation or coagulation that cannot be overcome by moderate stirring. | PASSES |
| Chem. & Physical Analysis | | |
| - Non Volatiles % | 43-47% | PASSES |
| - Ash Non Volatiles % | 42-52 | PASSES |
| - Specific Gravity 25°C Min | 1.15 | PASSES |
| Drying Time | 8 Hr. Max. | PASSES |
| Adhesion & Resistance to Water | No Penetration or Loss of Adhesion | PASSES |
| Resistence to Heat | No Blistering or Sagging | PASSES |
| Flexibility | No Cracking or Flaking | PASSES |
| Resistence to Impact | No Chipping, Flaking or Cracking | PASSES |

Polymer Modified
MasterSeal (PMM)
SMT - 106

SealMaster
January 2009
Supercedes: SMT-106 (7/04)

PAVING AND SURFACING
Pavement Sealer

# Polymer Modified MasterSeal (PMM)

Mixing Procedures:
For optimum results PMM shall be mixed in accordance with the following mix design (based on 100 gallons for ease of calculation):

| | |
|---|---|
| PMM Concentrate | 100 gallons |
| Sand* | 400 lbs. |

*(40-60 mesh AFS)

NOTE: If required, a small amount of water may be added to facilitate application of mixed material.

Application: For optimum performance and durability apply two coats of PMM with sand. A third coat of PMM with sand may be applied to high traffic areas such as entrances, exits, and drive lanes.

Application Rate of Mixed PMM: Apply properly mixed PMM (PMM Concentrate, Sand, and Water - if needed) at a rate of .11 to .13 gallon per square yard (70-82 square feet per gallon) per coat.

Estimating Material Requirements: To estimate gallons of PMM Concentrate required to cover a specific area use the following coverage rate:
One gallon of PMM Concentrate will cover approximately 85-95 square feet (9.4 to 10.5 square yards) per coat when properly mixed as a sand-filled coat and applied.

Note: Coverage rates may vary due to pavement age and porosity.

Precautions: Both surface and ambient temperature shall be a minimum of 50°F. Temperature shall not drop below 50°F in a 24 hour period following application. New asphalt surfaces should be allowed to cure a minimum of four weeks under ideal weather conditions (70°F) before applying PMM. Keep Out Of Reach Of Children. Do not store unopened drums or pails in freezing temperatures.

## 6. AVAILABILITY & COST

Availability: PMM is supported by a nationwide network of SealMaster manufacturing facilities along with a national network of professional applicators.

Cost: Cost information can be obtained from a local PMM applicator. Contact SealMaster for the PMM representative in your area.

## 7. WARRANTY

SealMaster Industries warrants that PMM meets the chemical composition and performance requirements set forth in section 4. Liability to the buyer or user of this product is limited to the replacement value of the product only.

## 8. MAINTENANCE

Periodic cleaning of parking lot surface will ensure optimum product service life.

## 9. TECHNICAL SERVICES

Manufacturer: Complete product specifications, material safety data sheets, and technical assistance is available from SealMaster.

PMM Professional Applicators: Your local PMM applicator is available to provide on-site inspections and recommendations to meet your specific needs.

## 10. FILING SYSTEMS

- Sweet's Catalog
- Sweet's CD
- Sweet's Online
- Sweet's Directory
- SealMaster Online Specification at www.sealmaster.net
- Complete SealMaster Product and Equipment Catalog Available

The statements made on this specification sheet are believed to be true and accurate and are intended to provide a guide for approved application practices. As workmanship, weather, construction, condition of pavement, tools utilized, and other variables affecting results are all beyond our control, the manufacturer warrants only that the material conforms to product specifications and any liability to the buyer or user of this product is limited to the replacement value of the product only. The manufacturer expressly disclaims any implied warranties of merchantability or fitness for a particular purpose. Warranty is void on multi-coat applications if material made by other manufacturers is used with this product.

Form No.: SMT-106
Date: January 2009

SealMaster
Phone: 1-800-395-7325

**www.sealmaster.net**

**SealMaster**
**Pavement Products & Equipment**

POWERVOLT
The power for your systems

Back to Transformers Index Home Contact Us

# RectiZpower

**Rectified Power Transformer**
**Series: RP, DRP**

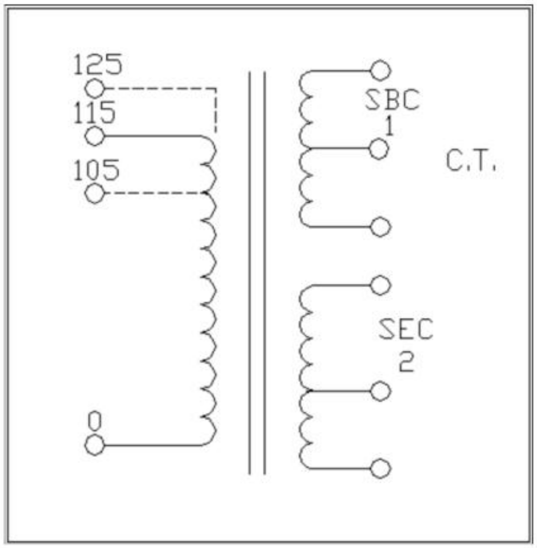
Standard Models Schematic Dimensions Cross reference

- **Ideal for rectifier application**
- **Single 115V or dual 115/230V, 50/60Hz Primary**
- **High isolation - 1500Vrms Hipot**
- **Two separate center-tapped secondaries for series or parallel connections**
- **American and Canadian Agency Approvals**

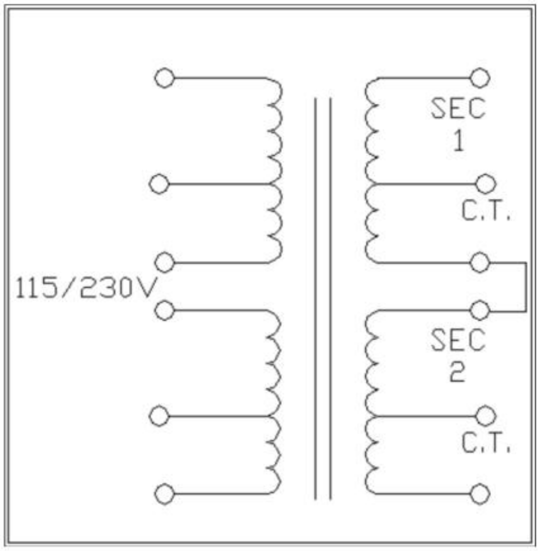
## Schematic

Return to TOP

**RP Schematic**

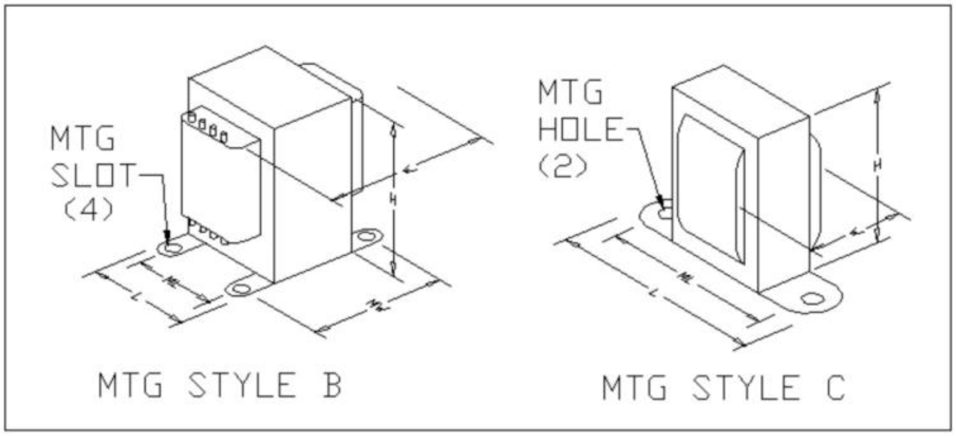


**DRP Schematic**



## Mechanical Drawings

Return to TOP



Dimensions

[under construction]

## Standard Models

Return to TOP

Voltage Selection Guide:
10volts 12volts 16volts 24volts 36volts 56volts 68volts 80volts

| Part Number Primary 50/60 Hz | | Secondary RMS Rating | | Mtg Style | L | W | H | ML | MW | Mtg Screw | Weight Lbs |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Single 115V | Dual 115/230V | Series | Parallel | | | | | | | | |
| **Series: 10 Volts and Parallel: 5 Volts** | | | | | | | | | | **Back** | |
| RP-10-1 | DRP-10-1 | 10VCT @ 1A | 5VCT @ 2A | C | 2.875 | 1.75 | 2.313 | 2.375 | - | #8 | 1.0 |
| RP-10-2 | DRP-10-2 | 10VCT @ 2A | 5VCT @ 4A | C | 3.125 | 2.125 | 2.75 | 2.813 | - | #8 | 1.5 |
| RP-10-4 | DRP-10-4 | 10VCT @ 4A | 5VCT @ 8A | C | 3.563 | 2.375 | 3.063 | 3.125 | - | #8 | 2.5 |
| RP-10-6 | DRP-10-6 | 10VCT @ 6A | 5VCT @ 12A | B | 3.375 | 2.75 | 2.813 | 2.813 | 2.125 | #8 | 3.5 |
| RP-10-8 | DRP-10-8 | 10VCT @ 8A | 5VCT @ 16A | B | 3.375 | 3.125 | 2.813 | 2.813 | 2.50 | #8 | 4.0 |
| RP-10-12 | DRP-10-12 | 10VCT @ 12A | 5VCT @ 24A | B | 3.75 | 3.25 | 3.125 | 3.125 | 2.50 | #8 | 5.0 |
| RP-10-25 | DRP-10-25 | 10VCT @ 25A | 5VCT @ 50A | B | 4.50 | 3.75 | 3.75 | 3.75 | 2.75 | #10 | 8.9 |
| **Series: 12.8 Volts and Parallel: 6.4 Volts** | | | | | | | | | | | **Back** |
| RP-12-1 | DRP-12-1 | 12.8VCT @ 1A | 6.4VCT @ 2A | C | 2.875 | 2.00 | 2.313 | 2.375 | - | #8 | 1.2 |
| RP-12-2 | DRP-12-2 | 12.8VCT @ 2A | 6.4VCT @ 4A | B | 3.00 | 2.50 | 2.50 | 2.50 | 2.00 | #8 | 2.5 |
| RP-12-4 | DRP-12-4 | 12.8VCT @ 4A | 6.4VCT @ 8A | B | 3.00 | 2.875 | 2.50 | 2.50 | 2.375 | #8 | 3.0 |
| RP-12-6 | DRP-12-6 | 12.8VCT @ 6A | 6.4VCT @ 12A | B | 3.375 | 3.063 | 2.813 | 2.813 | 2.50 | #8 | 4.0 |
| RP-12-8 | DRP-12-8 | 12.8VCT @ 8A | 6.4VCT @ 16A | B | 3.75 | 3.125 | 3.125 | 3.125 | 2.25 | #8 | 4.5 |
| RP-12-12 | DRP-12-12 | 12.8VCT @ 12A | 6.4VCT @ 24A | B | 4.125 | 3.25 | 3.438 | 3.438 | 2.375 | #10 | 6.0 |
| RP-12-25 | DRP-12-25 | 12.8VCT @ 25A | 6.4VCT @ 50A | B | 5.25 | 4.25 | 4.375 | 4.375 | 2.875 | #10 | 12.5 |
| **Series: 16 Volts and Parallel: 8 Volts** | | | | | | | | | | **Back** | |
| RP-16-1 | DRP-16-1 | 16VCT @ 1A | 8VCT @ 2A | C | 2.875 | 2.00 | 2.313 | 2.375 | - | #8 | 1.2 |
| RP-16-2 | DRP-16-2 | 16VCT @ 2A | 8VCT @ 4A | C | 3.125 | 2.25 | 2.75 | 2.813 | - | #8 | 1.8 |
| RP-16-4 | DRP-16-4 | 16VCT @ 4A | 8VCT @ 8A | B | 3.375 | 2.75 | 2.813 | 2.813 | 2.125 | #8 | 3.5 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RP-16-6 | DRP-16-6 | 16VCT @ 6A | 8VCT @ 12A | B | 3.75 | 3.125 | 3.125 | 3.125 | 2.25 | #10 | 4.5 |
| RP-16-8 | DRP-16-8 | 16VCT @ 8A | 8VCT @ 16A | B | 3.75 | 3.50 | 3.125 | 3.125 | 2.625 | #10 | 5.4 |
| RP-16-12 | DRP-16-12 | 16VCT @ 12A | 8VCT @ 24A | B | 4.125 | 3.875 | 3.438 | 3.438 | 3.00 | #10 | 8.0 |
| RP-16-25 | DRP-16-25 | 16VCT @ 25A | 8VCT @ 50A | B | 4.50 | 5.375 | 3.75 | 3.75 | 4.00 | #10 | 14.5 |
| **Series: 24 Volts and Parallel: 12 Volts** | | | | | | | | | | | **Back** |
| RP-24-1 | DRP-24-1 | 24VCT @ 1A | 12VCT @ 2A | B | 3.00 | 2.50 | 2.50 | 2.50 | 2.00 | #8 | 2.5 |
| RP-24-2 | DRP-24-2 | 24VCT @ 2A | 12VCT @ 4A | B | 3.00 | 2.875 | 2.50 | 2.50 | 2.375 | #8 | 3.0 |
| RP-24-4 | DRP-24-4 | 24VCT @ 4A | 12VCT @ 8A | B | 3.75 | 3.125 | 3.125 | 3.125 | 2.25 | #8 | 4.5 |
| RP-24-6 | DRP-24-6 | 24VCT @ 6A | 12VCT @ 12A | B | 4.125 | 3.25 | 3.438 | 3.438 | 2.375 | #10 | 5.8 |
| RP-24-8 | DRP-24-8 | 24VCT @ 8A | 12VCT @ 16A | B | 4.125 | 3.875 | 3.438 | 3.438 | 3.00 | #10 | 8.0 |
| RP-24-12 | DRP-24-12 | 24VCT @ 12A | 12VCT @ 24A | B | 4.50 | 4.50 | 3.75 | 3.75 | 3.375 | #10 | 11.0 |
| RP-24-20 | DRP-24-20 | 24VCT @ 20A | 12VCT @ 40A | B | 5.25 | 4.75 | 4.375 | 4.375 | 3.375 | 1/4 | 15.5 |
| RP-24-25 | DRP-24-25 | 24VCT @ 25A | 12VCT @ 50A | B | 5.25 | 5.625 | 4.375 | 4.375 | 4.125 | 1/4 | 19.5 |
| **Series: 36 Volts and Parallel: 18 Volts** | | | | | | | | | | | **Back** |
| RP-36-1 | DRP-36-1 | 36VCT @ 1A | 18VCT @ 2A | B | 3.00 | 2.75 | 2.50 | 2.50 | 2.25 | #8 | 2.6 |
| RP-36-2 | DRP-36-2 | 36VCT @ 2A | 18VCT @ 4A | B | 3.375 | 2.438 | 2.938 | 2.813 | 2.375 | #8 | 3.8 |
| RP-36-4 | DRP-36-4 | 36VCT @ 4A | 18VCT @ 8A | B | 4.125 | 3.375 | 3.438 | 3.438 | 2.625 | #10 | 7.0 |
| RP-36-6 | DRP-36-6 | 36VCT @ 6A | 18VCT @ 12A | B | 4.50 | 3.75 | 3.75 | 3.75 | 2.75 | #10 | 9.0 |
| RP-36-8 | DRP-36-8 | 36VCT @ 8A | 18VCT @ 16A | B | 4.50 | 4.50 | 3.75 | 3.75 | 3.375 | #10 | 11.0 |
| RP-36-12 | DRP-36-12 | 36VCT @ 12A | 18VCT @ 24A | B | 5.25 | 5.00 | 4.375 | 4.375 | 3.375 | 1/4 | 15.0 |
| RP-36-20 | DRP-36-20 | 36VCT @ 20A | 18VCT @ 40A | B | 6.375 | 5.375 | 5.313 | 5.313 | 3.375 | 1/4 | 23.0 |
| RP-36-25 | DRP-36-25 | 36VCT @ 25A | 18VCT @ 50A | B | 6.375 | 5.75 | 5.313 | 5.313 | 3.75 | 1/4 | 26.5 |
| **Series: 56 Volts and Parallel: 28 Volts** | | | | | | | | | | | **Back** |
| RP-56-1 | DRP-56-1 | 56VCT @ 1A | 28VCT @ 2A | B | 3.375 | 2.875 | 2.813 | 2.813 | 2.25 | #8 | 3.5 |
| RP-56-2 | DRP-56-2 | 56VCT @ 2A | 28VCT @ 4A | B | 3.75 | 3.25 | 3.125 | 3.125 | 2.50 | #8 | 5.0 |
| RP-56-4 | DRP-56-4 | 56VCT @ 4A | 28VCT @ 8A | B | 4.125 | 3.75 | 3.438 | 3.438 | 3.00 | #10 | 8.0 |
| RP-56-6 | DRP-56-6 | 56VCT @ 6A | 28VCT @ 12A | B | 5.25 | 4.25 | 4.375 | 4.375 | 2.875 | #10 | 12.0 |
| RP-56-8 | DRP-56-8 | 56VCT @ 8A | 28VCT @ 16A | B | 5.25 | 5.00 | 4.375 | 4.375 | 3.625 | 1/4 | 17.0 |
| RP-56-12 | DRP-56-12 | 56VCT @ 12A | 28VCT @ 24A | B | 6.375 | 5.25 | 5.313 | 5.313 | 3.375 | 1/4 | 22.0 |
| RP-56-25 | DRP-56-25 | 56VCT @ 25A | 28VCT @ 50A | B | 6.375 | 7.125 | 5.313 | 5.313 | 5.125 | 1/4 | 38.0 |
| **Series: 68 Volts and Parallel: 834 Volts** | | | | | | | | | | | **Back** |
| RP-68-1 | DRP-68-1 | 68VCT @ 1A | 34VCT @ 2A | B | 3.375 | 2.938 | 2.813 | 2.813 | 2.375 | #8 | 3.8 |
| RP-68-2 | DRP-68-2 | 68VCT @ 2A | 34VCT @ 4A | B | 4.125 | 3.375 | 3.438 | 3.438 | 2.625 | #10 | 7.0 |
| RP-68-4 | DRP-68-4 | 68VCT @ 4A | 34VCT @ 8A | B | 4.50 | 4.50 | 3.75 | 3.75 | 3.375 | #10 | 11.5 |
| RP-68-6 | DRP-68-6 | 68VCT @ 6A | 34VCT @ 12A | B | 5.25 | 5.00 | 4.375 | 4.375 | 3.375 | 1/4 | 15.0 |
| RP-68-8 | DRP-68-8 | 68VCT @ 8A | 34VCT @ 16A | B | 5.25 | 5.50 | 4.375 | 4.375 | 3.875 | 1/4 | 19.0 |
| RP-68-12 | DRP-68-12 | 68VCT @ 12A | 34VCT @ 24A | B | 6.375 | 5.75 | 5.313 | 5.313 | 3.75 | 1/4 | 27.0 |
| **Series: 80 Volts and Parallel: 40 Volts** | | | | | | | | | | | **Back** |
| RP-80-1 | DRP-80-1 | 80VCT @ 1A | 40VCT @ 2A | B | 3.375 | 3.063 | 2.813 | 2.813 | 2.50 | #8 | 4.0 |
| RP-80-2 | DRP-80-2 | 80VCT @ 2A | 40VCT @ 4A | B | 4.125 | 3.375 | 3.438 | 3.438 | 2.625 | #10 | 6.8 |
| RP-80-4 | DRP-80-4 | 80VCT @ 4A | 40VCT @ 8A | B | 5.25 | 4.25 | 4.375 | 4.375 | 2.875 | 1/4 | 12.5 |
| RP-80-6 | DRP-80-6 | 80VCT @ 6A | 40VCT @ 12A | B | 5.25 | 5.50 | 4.375 | 4.375 | 3.875 | 1/4 | 19.0 |
| RP-80-8 | DRP-80-8 | 80VCT @ 8A | 40VCT @ 16A | B | 6.375 | 5.25 | 5.313 | 5.313 | 3.25 | 1/4 | 20.5 |
| RP-80-12 | DRP-80-12 | 80VCT @ 12A | 40VCT @ 24A | B | 6.375 | 6.00 | 5.313 | 5.313 | 4.125 | 1/4 | 29.0 |

Return to TOP

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