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COMPREHENSIVE EVALUATION OF BRIDGE ANTI-ICING TECHNOLOGIES – FINAL REPORT

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Knik Arm is the northernmost branch of Cook Inlet. The Knik Arm Crossing Project is to construct a cost-affordable, vehicular toll bridge of about 2 miles across Knik Arm to join the Port of Anchorage and Port MacKenzie areas. Currently, only a single transportation corridor exists connecting the Anchorage and Mat-Su – the Glenn Highway. The Knik Arm Crossing Project will provide improved transportation infrastructure, vehicular access and connectivity and needed safety and transportation system redundancy.

Given the potential traffic disruptions caused by ice and snow in winter, a comprehensive literature investigation on bridge anti-icing and deicing technologies is critically needed. This report provides technical recommendations for viable and economic anti-icing and deicing technologies for the Knik Arm Bridge.

Based on the literature data in similar latitude, duration and intensity of freezing, and the fact that the thermal method may reduce the use of chemical agents substantially, a combination of the chemical method with a Fixed Automatic Spray Technology and the thermal method is suggested to be the best approach based on the cost-effectiveness criteria.

14- KEYWORDS : Anti-icing, Deicing, Bridge, Chemical Methods, Thermal Methods, Hot fluids, Road Weather Information System (RWIS), Fixed Automatic Spray Technology (FAST), Calcium chloride ($CaCl_2$),Sodium chloride (NaCl),Magnesium chloride ($MgCl_2$),Calcium magnesium acetate (CMA),Potassium acetate (KAc)

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DISCLAIMER

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EXECUTIVE SUMMARY

The Alaska Department of Transportation and Public Facilities (AKDOT&PF) in 2006 hired a team of consulting specialists to launch a project to investigate viable deicing and anti-icing techniques for the proposed bridge across Knik Arm.

Knik Arm is the northernmost branch of Cook Inlet. The Knik Arm Crossing Project is to construct a cost-affordable, vehicular toll bridge of about 2 miles across Knik Arm to join the Port of Anchorage and Port MacKenzie areas. Currently, only a single transportation corridor exists connecting the Anchorage and Mat-Su – the Glenn Highway. The Knik Arm Crossing Project will provide improved transportation infrastructure, vehicular access and connectivity and needed safety and transportation system redundancy.

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ACKNOWLEDGMENTS

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This report is the result of the concerted effort of several engineers and scientists at the University of Alaska Fairbanks (UAF), dedicated to evaluation of anti-icing and deicing technology for the proposed Knik Arm Bridge. Listed below are names and roles of the team members who performed this work, coordinated by Dr. Jing Zhang, Assistant Professor of Mechanical Engineering.

Anti-icing and Deicing Using Chemical Methods:

- Dr. Jing Zhang, Assistant Professor of Mechanical Engineering
- Dr. Rorik Peterson, Assistant Professor of Mechanical Engineering

Anti-icing and Deicing Using Thermal Methods:

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- Dr. Doug Goring, P.E., Professor of Mechanical Engineering at UAF and Acting Dean of the College of Engineering and Mines at UAF

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We would also like to thank Dr. Orson Smith, Professor of Arctic Engineering at the University of Alaska Anchorage (UAA) for sharing water measurement data, and Dr. Zhaohui (Joey) Yang, Assistant Professor of Civil Engineering at UAA for field trip assistance. Special acknowledgment is given to the AKDOT&PF officer and KABATA Chief Engineer, Mr. Verne Geidl, P.E., for his support of the program. Appreciation is also given to Mr. Billy Corner, P.E., Director of Alaska University Transportation Research Center (AUTC) who provided many useful suggestions during the stage of data collection and analyses. Their cooperation and experience were essential to the success of this project.

1. INTRODUCTION

The Alaska Department of Transportation and Public Facilities (AKDOT&PF) in 2006 hired a team of specialists to launch a two-phase project to investigate bridge deicing and anti-icing techniques for construction of a bridge across Knik Arm. Knik Arm is the northernmost branch of Cook Inlet. The Knik Arm Crossing Project is to construct a cost-affordable, vehicular toll bridge of about 2 miles across Knik Arm to join the Port of Anchorage and Port MacKenzie areas (Figure 1). Given the potential traffic disruptions caused by ice and snow, a comprehensive literature investigation on bridge anti-icing and deicing technologies is critically needed.

Figure 1: Map of the proposed Knik Arm Bridge (highlighted in white line) [2]

There are two distinct snow and ice control strategies that break or weaken the bonds holding ice and snow to a bridge surface: deicing and anti-icing. They differ in their fundamental objective. Whereas anti-icing operations are conducted to prevent the formation or development of bonded snow and ice for easy removal, deicing operations are performed to break the bond of already-bonded snow and ice. Deicing is familiar to most agencies since it has been the most widely used strategy in the past. The design of deicing operations as a bond-breaking operation stems from its timing: it is commonly initiated only after 25 mm (1 in) or more of snow has accumulated and bonded to the road.

Anti-icing is the snow and ice control practice of preventing the formation or development of bonded snow and ice by timely applications of a freezing-point depressant. It provides an efficient capability for maintaining roads in the best conditions possible during a winter storm. As a consequence, anti-icing has the potential to provide the benefit of increased traffic safety at the lowest cost. However, to achieve this benefit the maintenance manager must adopt a systematic approach to snow and ice control and must ensure that the performance of the operations is consistent with the objective of preventing the formation or development of bonded snow and ice. Such an approach requires good judgment in making decisions, requires that available information sources be utilized methodically, and requires that the operations be anticipatory or prompt in nature [3].

In contrast to anti-icing operations, deicing is the traditional practice of snow and ice control which involves waiting until an inch or more of snow accumulates on the pavement before beginning to plow and treat the highway with chemicals and/or abrasives. While this procedure is straight-forward, it frequently leads to a compacted snow layer that is tightly bonded to the pavement surface. A subsequent deicing of the pavement is then necessary, usually requiring a large quantity of chemicals to work its way through the pack to reach the snow and pavement interface and destroy or weaken the bond. Because this operation is reactionary, it requires less decision making than anti-icing. Yet as a result of its inherent delay, it often provides less safety at higher cost than anti-icing. Nonetheless, the reactive technique of deicing will remain important for snow and ice control, as there will always be lower priority service levels that preclude preventive operations [3]. Anti-icing is well suited to routes with a higher level of service. This is because the vigilance and timeliness of successful anti-icing operations are most compatible with service levels requiring earlier and higher frequency winter maintenance operations. It is also because the preventive nature of anti-icing can support higher service level objectives such as maintaining bare pavement throughout a storm or returning to bare pavement as soon as possible following pack formation [3].

1.1 Objective

This report is aimed at providing information for successful implementation of an effective anti-icing and deicing practice for the Knik Arm Bridge. The investigation was conducted from October 1, 2006 to January 31, 2007, and this report is written to guide the maintenance manager of the Knik Arm Bridge in developing a systematic and efficient practice for maintaining bridge pavement in the best conditions possible during a winter storm. It describes the significant factors that should be understood and must be addressed in an anti-icing program, with the recognition that the development of the program must be based on the specific needs of the site or region within its reach. It focuses on the weather information, materials, and methods that will best address site conditions.

1.2 Scope and Organization

Following the Introduction, this report is divided in five sections plus appendix:

- Section 2 presents an international literature investigation of chemical methods, with analysis of approximate costs per freezing event and approximate system life-cycle length when applicable.

- Section 3 describes an international literature investigation of thermal methods, with analysis of approximate costs (including standby costs) per freezing event and approximate system life-cycle length when applicable;

- Section 4 describes other innovative anti-icing methods;

- Section 5 summarizes the collected structural, environmental and operation information of the Knik Arm Bridge;

- Section 6 provides a ranking of collected anti-icing technologies and a discussion of future directions.

Guidance for conducting anti-icing operations during specific precipitation and weather events is also included in Appendix I. Appendix II provides data on an innovative anti-icing system FAST (Fixed Automatic Spray Technology System) in use. Several case studies using thermal methods are also provided in Appendices III and IV

2. ANTI-ICING AND DEICING USING CHEMICAL METHODS

2.1 Chemical Methods

This Section describes the chemicals used in anti-icing and deicing practice. Information is presented on the properties of the five most commonly used chemicals for anti-icing treatments. The five chemicals are calcium chloride, sodium chloride, magnesium chloride, calcium magnesium acetate, and potassium acetate. They are listed here with their eutectic temperatures and concentrations:

Table 1: Eutectic temperature and eutectic concentration of five chemicals [3]

Chemical	**Eutectic temperature °C (°F)**	**Eutectic concentration %**
Calcium chloride ($CaCl_2$)	-51 (-60)	29.8
Sodium chloride (NaCl)	-21 (-5.8)	23.3
Magnesium chloride ($MgCl_2$)	-33 (-28)	21.6
Calcium magnesium acetate (CMA)	-27.5 (-17.5)	32.5
Potassium acetate (KAc)	-60 (-76)	49

The freezing point is the temperature at which a given solution will freeze, and depends on chemical concentration. The eutectic temperature is the lowest freezing point attainable for a given product and occurs at the eutectic concentration. Because the concentration is constantly changing as ice melts, it is not possible to maintain the eutectic concentration and the effective working temperature of any chemical is higher than the eutectic temperature.

In order for a chemical to act as a freezing-point depressant, it must go into solution. A solid chemical applied as an anti-icing treatment must cover the highway pavement surface as rapidly as possible in solution form to act as a barrier to the formation of a bonded snow or ice layer anywhere on the road.

Energy is required to initiate the solution process and to continue the melting process. The solution process, in the case of salt, will take place very slowly. A dry particle of salt placed on a dry surface will just sit there for a time until it can absorb enough thermal energy from the surrounding environment to a point where a liquid film is formed on the surface of the particle. This initial brine then triggers the solution of the rest of the salt. As the particle dissolves, it continues to absorb thermal energy from its surroundings. This type of absorption process is called an endothermic reaction.

The rate at which salt goes into solution can be accelerated by several means. It can find free moisture or liquid on the pavement surface to start the brine generation process. Alternatively, a liquid can be added to the surface of the salt particles before they are placed on the pavement surface. This second means of applying a liquid to dry salt is accomplished by a prewetting process.

The solution process of calcium chloride takes place much faster than that of salt. This is because calcium chloride is both hygroscopic and deliquescent ($CaCl_2$ will absorb moisture at a relative humidity (RH) of 42 percent and higher; NaCl will not begin to absorb moisture until a RH of 76 percent is reached). Thus, solid calcium chloride will absorb moisture from the air until it dissolves. The brine solution will continue to absorb moisture until an equilibrium is reached between the vapor pressure of the solution and that of the air. If the humidity of the air increases, more moisture is absorbed by the solution. If the humidity of the air decreases, water evaporates from the solution to the air.

As the particle of calcium chloride dissolves, it releases a considerable amount of heat. This type of process is called an exothermic reaction.

When calcium chloride and salt are combined, they complement each other as snow and ice control chemicals. When combined, the deliquescent calcium chloride absorbs moisture from its surroundings releasing heat and thereby increasing the rate of solution of sodium chloride. These reactions produce brine quickly which sustains the continued brine generation of the two chemicals.

The solubility of all chemicals varies with temperature. A lower temperature results in a lower solubility. This decrease in solubility has a limit, a point where no more of the chemical can dissolve and depress the freezing point.

Graphing the eutectic temperature which concentration produces a phase diagram, from which the optimum eutectic temperature may be determined. The freezing-point of a brine can best be described by reference to the phase diagram of a generic salt-water solution shown in the small plot inserted in the lower left of Figure 2. The solid curve is a plot of concentration of a salt (X-axis) versus temperature (Y-axis). The solid curve separates the phases of the solution. Above this curve, the salt is totally in solution. The lowest temperature on the curve is called the temperature at the eutectic point, or eutectic temperature. Below this temperature (and below the dashed line), no solution exists, only a mixture of ice and solid salt. A mixture of ice and salt solution exists to the left of the solid curve and above the dashed line. A mixture of solid salt and salt solution exists to the right of the solid curve and above the dashed line. Thus, the solid curve describes the freezing-point of a brine as a function of the concentration of the salt solution.

Some comments are given below about the important characteristics of the generic phase diagram.

1. The freezing-point of the brine solution decreases with increasing concentration up to the eutectic composition. The freezing-point of the brine solution will increase as the concentration increases beyond the eutectic composition.
2. Brine solutions of a concentration less than the eutectic composition have a freezing-point lower than the melting temperature of pure ice or 0^oC (32^oF).

3. In snow and ice control operations and particularly during anti-icing treatments, it is necessary to operate with brine solutions as close as possible to, but less than, the eutectic composition. The brine solution concentration will decrease as it is diluted with water from either the melting of snow/ice or falling rain/freezing rain. Consequently, it is important to monitor the dilution process so that the solution concentration does not decrease to a value which corresponds to a temperature in the freezing temperature range above the pavement temperature. When this occurs, a refreeze of the solution will take place.

Calcium chloride ($CaCl_2$):

Calcium chloride is available as an aqueous mixture or anhydrous solid. The aqueous mixture is commonly referred to as liquid calcium. It is primarily used as a pre-wetting agent for use with rock salt and dust control. A 2003 laboratory study by the Maine DOT concluded that the addition of liquid calcium to rock salt did not significantly increase the rate of deicing except in the first 5-10 minutes after applications, and therefore could not justify it's added cost to traditional salt [4]. Although more expensive than rock salt, liquid calcium is relatively inexpensive and usually shipped in bulk truck tanks, railcars or barge. Liquidow™ is a widely used commercial liquid calcium product from Dow. The eutectic temperature is -51°C at a concentration of 30%.

Sodium chloride (NaCl):

Sodium chloride is also known as rock salt, was the first deicing chemical widely used, and is by far the least expensive. Use of NaCl has declined recently because other chemicals have proven more effective and less detrimental. Brine usually refers to the liquid that forms when NaCl and water are mixed, and the concentration of NaCl in brine can vary. NaCl can accelerate corrosion rates of both automobiles and steel reinforced concrete. The addition of organic anti-corrosion agents has been moderately effective in reducing the rate of accelerated corrosion. NaCl can damage poorly designed hot-mix asphalt, cement, and concrete. There are also some reports that brine seeping into road cracks can cause differential frost heaving [5]. The operating temperature of NaCl is higher than most chemicals, with a eutectic temperature of -21°C at a concentration of

23%. A pre-wetting fluid is often used when applying solid rock salt to help initial adherence and prevent it from bouncing off the road. Abrasives such as sand and cinders are often applied at the same time to increase traction. Excessive use of abrasives can have some adverse environmental effects including decreased air quality.

The phase diagrams of NaCl and $CaCl_2$ solutions are presented in Figure 2. As can be seen, the eutectic temperature of the calcium chloride-water system is lower than the eutectic temperature of the sodium chloride-water system. The eutectic composition of the calcium chloride-water system is approximately 30 percent $CaCl_2$ and 70 percent H_20 by weight which remains a solution as low as -51°C (-60°F). The eutectic composition of the sodium chloride (common road salt)-water system is 23 percent NaCl and 77 percent H_20 by weight, which freezes at about -21°C (-6 °F).

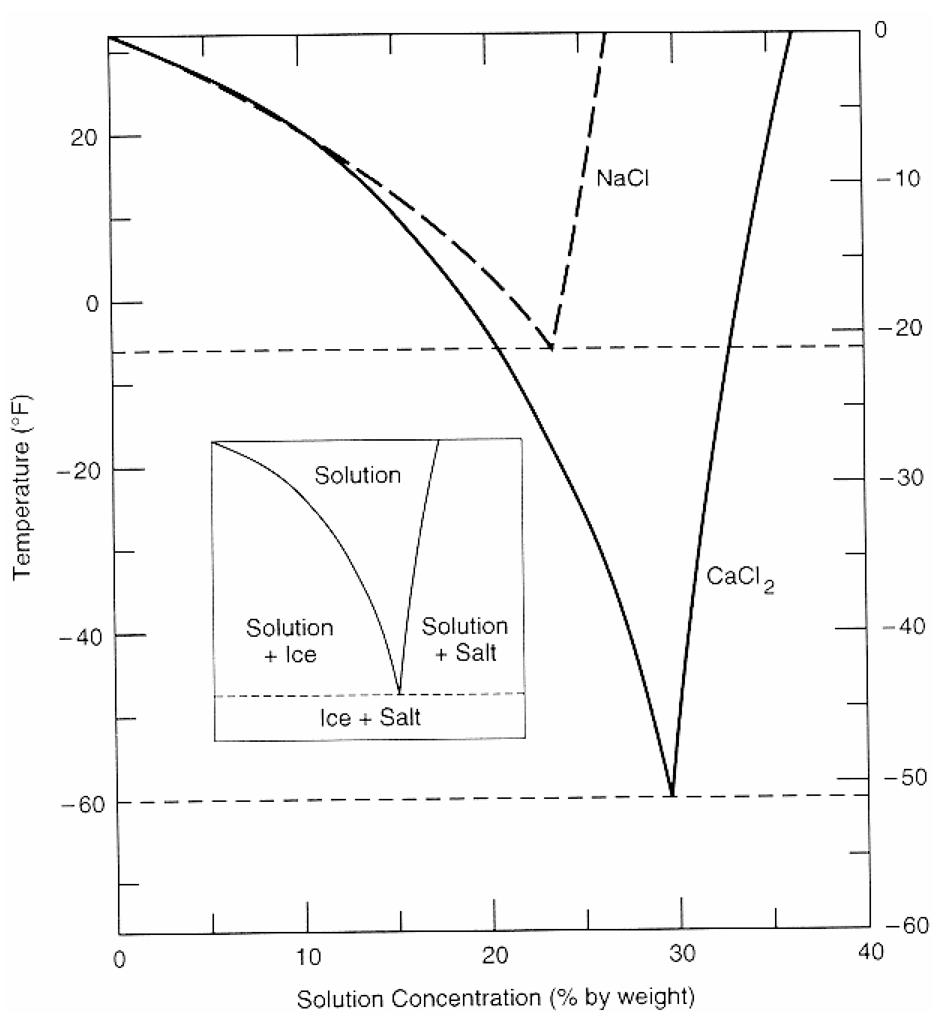

Figure 2: Phase diagrams of NaCl and $CaCl_2$ solutions.

Magnesium chloride ($MgCl_2$):

Magnesium chloride is very similar to NaCl. Additionally, the magnesium may react with cement paste in concrete and weaken the structure. In 2004, Maine DOT compared a commercial liquid $MgCl_2$ product Ice B'Gone®, which contains an organic anti-corrosion agent as well. Plow operators reported that the product performed better than both liquid calcium and $CaCl_2$ in both deicing and anti-icing applications [5]. A similar 2006 Maine DOT study found contradicting results about the commercial product Meltdown® 30, where negative reports indicated that deicing was required soon after application [6].

The phase diagram of magnesium chloride, $MgCl_2$, solutions is presented in Figure 3 together with those of CMA, KAc, and the chloride solutions discussed above. The eutectic temperature of the magnesium chloride-water system is between that of NaCl and $CaCl_2$. The eutectic composition for the magnesium chloride-water system in this figure is 21.6 percent $MgCl_2$ and 78.4 percent H_20 by weight which freezes at about -33°C (-28°F). The density and chemical composition of $MgCl_2$ brines can vary somewhat with the source of $MgCl_2$ and with seasonal weather fluctuations which affect the solar evaporation process used in the production of flake $MgCl_2$. The chemical composition of $MgCl_2$ brines can include, in addition to magnesium and chloride, such components as sulfates, sodium, potassium, lithium, bromine, and iron. Consequently, some differences can occur between individual phase diagrams of commercially available magnesium chloride-water systems.

Calcium magnesium acetate (CMA):

Calcium magnesium acetate is produced from acetic acid, a petroleum-based product, and causes CMA to be relatively more expensive than the chloride salts. The operating temperature of CMA is lower than chloride chemicals with a eutectic temperature of -28°C at a concentration of 32.5%.

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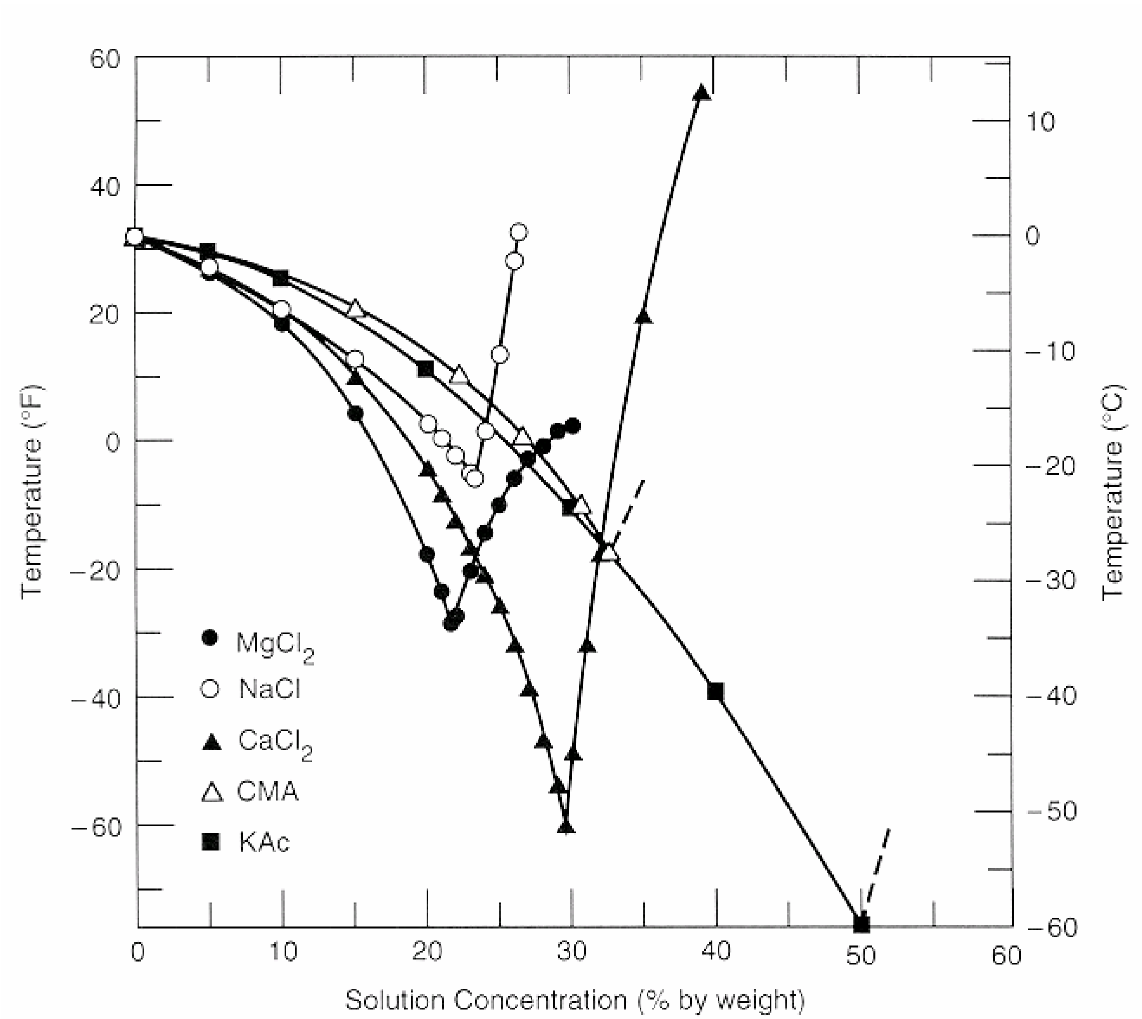

Figure 3: Phase diagrams of five chemical solutions.

Calcium magnesium acetate (CMA):

Calcium magnesium acetate is produced acetic acid, a petroleum-based product, and causes CMA to be relatively more costly than the chloride salts. The operating temperature of CMA is lower than chloride chemicals with a eutectic temperature of -28C at a concentration of 32.5%.

Potassium acetate (KAc):

Potassium acetate is a chemical product which biodegrades to CO_2 and H_2O. It works effective down to -20°C and its eutectic temperature is -75°C. The recommended application rate is 0.5 gal/1000 ft^2 for anti-icing and 1.0 gal/1000 ft^2 for deicing [7]. KAc has been recommended as a replacement for glycol-based chemicals on airport runways due to a decreased environmental impact. It is compatible with stainless steel, not brass, aluminum or cast iron. It is also compatible with rubber and PVC. Cryotech E36 is a common commercial product of KAc.

Currently commercial sources for CMA use the reaction of acetic acid with dolomitic limestone for production. The acetic acid, the costly component of the compound, is manufactured from natural gas or petroleum, though small quantities have been produced by biodegradation of agricultural wastes. The compound is available as pellets. Though not as soluble in water as NaCl and $CaCl_2$, solutions can be made at point of use for use as a prewetting agent or straight chemical application. It is not a highly effective deicing chemical in solid form because of its affinity for water and its light particle mass. Its benefit is that snow is made mealy and will not compact. CMA is primarily a mixture of calcium and magnesium acetates, produced with a 3/7 Ca/Mg ratio which was found to be optimum in previous FHWA studies. The eutectic temperature is about -28^{o}C (-18^{o}F) at a concentration of 32.5 percent.

Potassium acetate, or KAc as it is commonly known, is produced by the reaction of acetic acid with potassium carbonate. The sources of acetic acid are the same as are used in the production of CMA. Potassium carbonate is one of the groups of salts commercially known as potash. Potassium carbonate is currently produced by one of several processes that use potassium chloride, another salt of the potash family. The compound, potassium acetate, is a white, crystalline, deliquescent powder that has a saline taste. It is soluble in water and alcohol. Solutions are alkaline under a litmus test. The dry compound is combustible but is used as a dehydrating agent, a reagent in analytical chemistry, and in the production of synthetic flavors, in addition to other uses. The eutectic temperature of a KAc and water solution is -60°C (-76°F) at a concentration of 49 percent. A commercial form of liquid KAc, containing a 50 percent concentration by weight plus corrosion inhibitors, has been used as a prewetting agent with dry salt or as a straight chemical application. Some experience has been gained with the straight liquid form during anti-icing experiments.

The curve for CMA (Figure 3) was determined from different concentration solutions made by dissolving commercially available CMA supplied in a dry pellet form. The curve for KAc was determined using a commercially available liquid form of KAc. The eutectic temperature for the CMA-water system in Figure 3 is -27.5°C (-17.5°F) at a concentration of 32.5 percent. The eutectic temperature for the KAc-water system is -60°C (-76°F) at a concentration of 49 percent. The curves for CMA and KAc almost coincide with each other. Also, they have a much flatter slope than the other three curves. This is an important feature of both CMA and KAc solutions. The refreeze temperature of both CMA and KAc solutions rises slower with dilution than do the refreeze temperatures of NaCl, $CaCl_2$, or $MgCl_2$. This feature makes them well suited for use in a liquid form during anti-icing treatments. This is especially true for their use in a liquid form for the pretreatment of bridge decks in anticipation of frosting, or localized icing conditions.

There are drawbacks to the use of CMA or KAc compared to traditional salts. A much higher concentration of either CMA or KAc solution is needed than the corresponding concentration of NaCl at a given temperature to keep the solutions from refreezing. The solution concentration of CMA must be 1.41 times higher than the NaC1 solution concentration at -9.4°C (15°F) (19 percent for CMA versus 13.5 percent for NaCl) to keep both solutions from refreezing. This factor increases to 1.54 at -3.9°C (25°F). The solution concentration of KAc must be about 1.37 and 1.38 higher than the NaCl solution concentrations at -9.4°C (15°F) and -3.9°C (25°F), respectively. These differences in concentrations needed for both CMA and KAc translate into considerably higher costs per application treatment for both chemicals than NaCl.

In spite of the popularity of anti-icing and deicing chemicals, caution should be practiced before application in large quantities. Many chemicals can cause corrosion of bridge components. Road salt is most clearly damaging to bridge decks [8]. The chloride ions in salt penetrate concrete and cause reinforcing steel bars (rebar) to rust, resulting in cracking and fragmentation of the surrounding concrete. The second one is that prewetted anti-icing chemicals. Prewetted anti-icing chemicals can dramatically reduce the required quantity of salts. A 50 percent reduction in salt consumption in the Bavarian State of Germany has been cited, while maintaining the same levels of service achieved with dry salt. Approximately 10 percent of the Bavarian snow and ice control material spreading equipment fleet is being converted annually to allow the use of prewetted, liquid, or mixed materials [9]. However, use of liquid anti-icing chemicals can have the undesirable effect of actually causing blowing snow to adhere to the road or bridge surface when it would otherwise blow over it. This is a potential problem on the Knik Arm Bridge that could be accommodated for with a RWIS system (see Section 4).

There is also a two-step de-icing/anti-icing practice where the first step is performed with de-icing fluid. The correct fluids are chosen with regard to ambient temperature. After de-icing, a separate over-spray of anti-icing fluid is applied to protect the relevant surfaces, thus providing maximum possible anti-ice capability. The second step is performed with anti-icing fluids which may differ from deicing fluids. The correct fluid concentration is chosen with regard to desired holdover time and is dictated by outside air temperature and weather conditions (see tables 1 and 2). The second step should be performed before fluid from step one has time to refreeze, typically within three minutes. Depending on weather conditions, the recommend the two-step operations are summarized in Appendix I.

2.2 Cost Analysis of Various Chemical Methods

Sodium chloride (NaCl) has been used as an ice-control chemical on roads since early in this century. It is produced by three processes: rock salt is mined by conventional hard rock mining equipment and techniques; solar salt is produced by the evaporation of sea water and may contain only a small amount of impurities; and evaporated or solution or vacuum salt, a very pure form made by drying under vacuum the solution resulting from injection of water into deep underground deposits. Most salt used for highway applications in the United States is rock salt, though some solar salt is produced in several western states and some is imported into the eastern US. Naturally occurring rock salt is the mineral halite, and usually contains between 1 percent and 4 percent impurities, mostly gypsum, shale, dolomite, and quartz. The price is about $30 per ton [8].

CMA (Calcium Magnesium Acetate) is produced by reacting acetic acid with dolomitic lime. Whereas dolomitic lime is abundant and inexpensive, acetic acid is far more costly. Currently, the most economical method of producing acetic acid is by using natural gas as a feedstock. After spending several years investing alternative processes for producing CMA, the Federal Highway Administration (FHWA) and most states now relay on industry for further development. Chevron Chemical Company is currently the only commercial producer of CMA. It makes a palletized product in which the acetate is derived from natural gas. The price in 1991 was $ 600 to $700 per ton delivered to reflect projected full-scale production costs [8]. A summary of the cost of deicing chemicals are given in Table 2.

Table 2: Cost of deicing chemicals and their temperature range and application rate [1].

Deicing Chemical	**Temperature Range**	**Application Rate**	**Approximate Cost in Volume**	**Approximate Cost in Area**
Sodium chloride (NaCl)	-10°C to 1 °C (14 °F to 34 °F)	13 to 68 g/m^2 (170 to 890 lb/12ft lane-mile)	\$29/m^3 (\$26/ton)	\$0.0003/m^2
Calcium chloride ($CaCl_2$)	-25 °C (-13 °F)	Not used alone in the U.S.A	\$294/ m^3 (\$267/ton)	\$0.03/m^2
Salt mixed with Calcium chloride ($CaCl_2$)	-17 °C to 0 °C (0 °F to 32 °F)	21-50 l/m^3 salt (5 to 12 gal/ton)	\$108/ m^3 (\$98/ton)	\$0.01/m^2
Calcium Magnesium Acetate (CMA)	-5 °C to 0 °C (23 °F to 32 °F)	15 to 39 g/m^2 (200 to 500 lb/12ft lane-mile)	\$738/ m^3 (\$670/ton)	\$0.004/m^2

Urea	-9 °C (16 °F)	26 to 136 g/m^2 (340 to 1780 lb/12ft lane-mile)	\$145-\$290/ m^3 (\$130-\$260/ton)	\$0.007/m^2
Magnesium chloride	-15 °C (5 °F)	8 to 11 g/m^2 (100 to 150 lb/12ft lane-mile)	Not Available	\$0.0002/m^2
Formamide	-18 °C (0 °F)	Not Available	\$290-\$435/ m^3 (\$290-\$390/ton)	\$0.002/m^2

The gross estimate of the deicing strategy is approximately $2,500/lane-mile [10]. The primary portion of the figure includes standby cost and labor. Based on the design of the Knik Arm Bridge (4 lane, 2 miles), the cost of each storm would be $20,000 per storm. Please note that standby cost of chemical method is comparatively lower than other methods. Labor cost can also be cut substantially if innovative methods, for example, Fixed Automatic Spray Technology (FAST, see Section 4), are applied.

There is no consistent data about the number of winter storms in Anchorage. It is reasonable to assume a snow storm in every two weeks from October to March. Then the total number of snow storms is about 15/year. The cost of deicing would be $300,000 per year. Please note that chemical methods are much more effective and cost-effective compared to thermal methods at low temperatures.

3. ANTI-ICING AND DEICING USING THERMAL METHODS

3.1 Thermal Methods

There is some concern for the environmental impact of chemicals on soil, ground water, and biochemical oxygen demand, and the potential corrosion of bridge deck structures and reinforcing bars when chemicals are used. Considering the environmental consequence of chemical deicing/anti icing agents on the surroundings a decision should be made. Using the thermal methods are an attractive method to reduce the use of chemical agents substantially may prove to be an alternative, which have been investigated and used occasionally [11]. Several types of pavement heating method have been explored and they are discussed below.

Electrically Conductive Concrete:

Yehia and Tuan [1] discuss a type of composite made up of steel fiber, steel shavings and regular concrete. About 15 % of the conductive material by volume is mixed with concrete to make this compound. The metallic components provide a higher electrical conductivity. When electrical power is applied to this conductive concrete, heat is generated due to the electrical resistance of the metallic particles and steel fibers. In a design presented by Yehia and Tuan [1], a 2-inch thick conductive concrete is overlaid on top of a 6-inch thick regular concrete deck. A thermal insulation layer between the conductive concrete and the regular concrete deck is provided to minimize the heat loss into the bridge deck. Therefore, the heat is directed into the ice layer above the conductive concrete causing the ice to melt.

Electrical Resistive Heating:

Electrical heating wires can be embedded below the surface of the pavement in the wheel track regions of the lanes. There should be several strands of wire running parallel along the wheel track. With surface mounted sensors or cameras detecting frost or snow on the pavement, these wires will be activated to help melt the snow and ice and prevent the formation of black ice. The Ladd Canyon Heating Project by Oregon Dept of Transportation [12] is testing this method for a one-mile section on I-84.

In Japan, at locations where pavement freezing poses a significant hazard such as at sharp curves, the pavement is heated using electric resistance wiring or pipes embedded in the road that carry hot water from nearby manufacturing plants or naturally occurring hot springs. This same technique has been used in urban areas for crosswalks and sidewalks [9].

Geothermal Heat Pumps:

In this system, heat is extracted from the ground by a ground loop heat exchanger. The heat is transferred to a propylene glycol mixture in a series of heat exchangers, which is then circulated throughout the bridge deck for deicing purposes. Spitler and Ramamoorthy [13] discuss such a system for deicing a bridge deck in Oklahoma. The hydronic fluid is circulated via polyethylene tubes embedded in the bridge deck in a serpentine fashion. The tube size is 18 mm dia spaced 300 mm apart placed 75 mm below road surface. The deck thickness is 200 mm. For a bridge deck of 215 m × 12 m being heated on the west bound side, sixteen 106 kW heat pumps are required. Since the Anchorage ground temperature is colder than Oklahoma, the available ground thermal energy may not be sufficient to favor this design, even though recharging the ground during the summer by the heat from the bridge deck is a possibility.

In Japan, techniques involving the use of sprinkler systems have been developed to control snow accumulations. In this process, low-velocity, low-pressure systems are activated during snowfall when the ambient and pavement temperatures are just above or approach the freezing point. The constant flow of warm water over the pavement surface prevents snow accumulation and melts the deposited snow to allow runoff into the conventional storm sewer system [9].

Infrared Heating:

Infrared heaters can be mounted on a truck or on the bridge side structures and their beams are directed from these lamps to the snow and ice on the bridge deck to melt it. Switzenbaum et al. [11] briefly discuss this system for aircraft deicing.

Microwave & Radio Frequency Power:

Other power sources under consideration are the microwave and radio frequencies (RF). Similar to a microwave oven, microwave beams can be focused from a truck mounted system [14] or from bridge structures onto the iced surface to heat and melt it. Likewise RF resonators may be vehicle mounted or bridge side mounted and excited to generate enough heat to be absorbed by ice and snow resulting in melting.

Solar and Wind Power:

Photovoltaic cells may be considered for augmenting electric power on the bridge in climates where sunlight is sufficient in winter. However, for the Knik Arm Bridge location, solar energy collection may not be feasible in the winter. However, the wind speed prevailing over the bridge may be enough to run small-scale wind turbines to generate electricity that can be used to supplement the electrical energy needed for deicing the bridge deck.

3.2 Cost Analysis of Various Thermal Methods

The estimated cost of primary thermal methods is given in Table 3.

Table 3: The cost estimates for various heating systems are cited from Yehia and Tuan [1].

Heating	Approximate Cost	Annual Operating Cost	Power Consumption
Infrared Heat Lamp	$96/m^2$ ($8.9/ft^2$)	Not Available	75 W/m^2 (7 W/ft^2)
Electric Heating Cable	$54/m^2$ ($5/ft^2$)	$4.8/m^2$ ($0.45/ft^2$)	323 –430 W/m^2 (30-40 W/ft^2)
Hot Water	$161/m^2$ ($15/ft^2$)	$250 / Storm, 3 inch snow	473 W/m^2 (44W/ft^2)
Heated Gas	$378/m^2$ ($35/ft^2$)	$2.1/m^2$ ($0.2/ft^2$)	Not Available
Conductive Concrete Overlay	$48/m^2$ ($4.5/ft^2$)	$5.4/m^2$ ($0.5 ft^2$)	516 W/m^2 (48 W/ft^2)

4. OTHER INNOVATIVE TECHNIQUES

In addition to the techniques discussed in Sections 2 and 3, there are many other strategies and techniques that can or have been used in snow and ice control operations.

Fixed Automatic Spray Technology (FAST):

Primary components of the Fixed Automatic Spray Technology (FAST) are a storage tank, pump house, piping, nozzles, and control assembly. Piping should be synthetic rubber to avoid corrosion. Nozzle fittings should be stainless steel or brass to avoid corrosion. Flush-mounted surface pavement nozzles can spray up to 30 feet (~10 meters) in a radial direction. The control assembly should be capable of activating automatically by the RWIS (Road Weather Information System) or manually, and possibly remotely by a pager, wireless phone, or computer network connection. Pavement sensors use electrical conductivity, surface temperature and optical measurements to monitor roadway surface conditions. A dynamic message sign is usually installed at both ends of the road or bridge to warn motorists when the system is in use. There were over 25 FAST systems in over 5 states as of 2000, a summary table from the Snow and Ice Pooled Fund Cooperative Program (SICOP) is in Appendix II. As of 2004, 23 states either have FAST systems or are planning on installing them [15].

Road sensors are an instrumental part of a FAST system, and can be either passive or active. Passive sensors are tuned for the type of deicing chemical used in order to properly determine the freezing point depression. Active sensors use a peltier junction and can accurately measure the freezing point independent of the type of chemicals being used.

A 2002 survey of maintenance crews responsible for FAST systems indicated that the addition or improvement of visual monitoring devices such as mounted video cameras would be beneficial.

A FAST system manufactured by Odin was installed in 1997 on a two-lane interstate bridge in Corbin, KY [16]. Nozzles are installed on the bridge walls and rails and not in the road surface. Each application uses eight gallons and is activated less than 5 times per year on average due to the relatively temperature climate. Spraying takes about 10 seconds per applications. The deicing solution is aqueous calcium chloride. Activation occurs using a combination of RWIS and visual observations on a locally-mounted video camera.

The O'Neal bridge over the Tennessee River in Alabama installed a FreezeFree system Energy Absorption Systems (owned by Quixote) in 2002 [17]. The 4-lane bridge is 2000 feet long. There are 114 nozzles that disperse 100 gallons on CMA in 20 minutes. A RWIS automatically triggers the system. Overhead signs warn motorists when the system is in use.

The 2000-foot, eight-lane bridge over the Mississippi River in interstate I35 in Minneapolis MN installed a FAST system in 1999 [18]. The Swiss company Boschung Inc. installed the system, which cost $578,000 for installation, hardware, and software. The KAc-based commercial product CF7® is used. An average winter season is 150 days, and the system was activated 218 times in a representative year. Each spray event required 34 gallons (12 gallons per lane mile). There are 76 median-mounted nozzles and 68 embedded nozzles in both directions spaced every 55 feet [19]. Warning lights indicate when the system is in use. A 2-year study of weather and activation indicated no correlation between amount of snowfall and number of sprays. After installation, a 68% reduction in the winter-related crashes was recorded. Fluids in the system are replaced with water during the summer and operated once a month for maintenance.

The Kansas interchange of K-156 and US highway 50 installed a FAST system in 2000 and is activated remotely by a pager [20]. There is no RWIS. The system was installed by Odin and used Cryotech® CMAK (calcium magnesium acetate with potassium). Nozzles spray for two seconds in two intervals in case a passing car interferes with the original application.

Three FAST systems were installed in Pennsylvania The Warren County Bridge has 25 crashes in the two years before installation. There were zero crashes in the year after installation. Average cost for these bridges is $150,000 [21]. Pennsylvania Dept. Transportation recommends installation on roads and bridges that have many of the following attributes: history of snow/ice related crashes, less than 2.5% grade, susceptible to black ice and frost, speed limit greater than 45 mph, high daily traffic volume, and ability to accommodate the anti-icing system. The proposed Knik Arm Bridge meets most of these criteria.

A literature review was conducted for the Nebraska Dept of Roads of existing FAST systems implemented in other states. Based on systems in Utah, Minnesota, and Kentucky, the average benefit-cost ratio is 1.8 to 3.4, and reduction on accident frequency ranged from 25 to 100 percent [22]. A survey of state transportation agencies indicated that 8 of 19 responding states plan on, or already have, implemented FAST systems in their state.

In Europe, the FAST system is also called In-Pavement Chemical Distribution System. A large, in-pavement chemical distribution system was constructed in 1997 on the A9 Ring Road around Lausanne, Switzerland [23]. The highway carries about 5,000 trucks daily. The 8.3 km of pavement on the highway was constructed with drainage (porous) asphalt for reduction of spray during wet weather but primarily of noise reduction. The location and pavement used were natural choices for this type of chemical distribution system for the following reasons: (i) Porous asphalt normally requires more chemical applications to maintain safety in winter weather; and (ii) it is often congested during rush hour, making ice control difficult.

A central storage system of liquid salt holds 64, 000 liters, which is sufficient for 2 days of extreme use of ice control chemical. A computerized system contains 30 preprogrammed distribution plans, depending on precipitation and temperature, including anti-icing, with rates as low as 1 g/m^2. The spray distribution system is located in the middle of the concrete barrier, shown in Figures 4 and 5. The quantity and pressure required for each sprinkler head are preset and depend on precipitation and other factors. The sprinkler heads can be in the concrete barrier or between guard rails. A single, in-pavement nozzle can cover two lane sections. The nozzles are placed in line with the right lane. The heads are spaced about every 12 m. There are more than 1,000 heads in the section in Lausanne. If the system is not on porous asphalt or bridges, it can be spaced as follows:

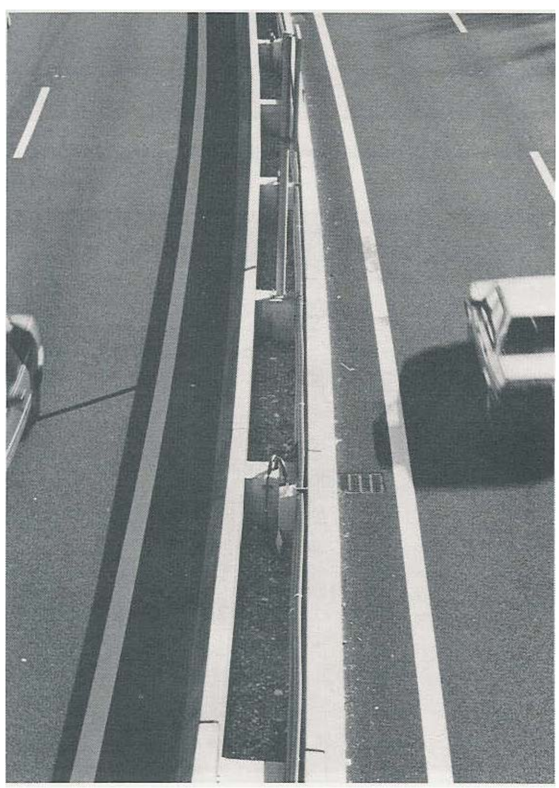

Figure 4: Looking down at piping for automated sprinkler system in concrete barrier.

Figure 5: Spray head in action, automated salt spraying system in Lausanne, Switzerland.

Road Weather Information System (RWIS):

Bridge decks often freeze before the adjacent roadway condition becomes hazardous and the mobile, truck-mounted anti-icing/deicing operations of the roadway are initiated. A guardrail-mounted system has been used in Europe for spraying snow and ice control materials onto a bridge deck. In such installations, the process is controlled by an automated loop that monitors both pavement and climate conditions, and responds by spraying materials that perform ice and snow control on the deck when needed.

Road weather information systems (RWIS) are small weather stations that provide specialized information on road surface conditions in addition to traditional weather data such as temperature, wind speed and direction, and humidity. They are able to monitor the presence of surface moisture, which is instrumental in determining when deicing needs to take place. RWIS is instrumental for effective anti-icing. There are three primary components of a RWIS, each contributing to the cost of the system: the pavement and air sensors, the electrical and computer hardware and software, and the information transmission lines or corresponding wireless hardware.

The Federal Highway Administration (FHWA) identifies three temperature ranges associated with potential icing situations: below 0°C during rain, snow or sleet; -2°C to +2°C for frost and black ice; and lower than -10°C during any precipitation [24]. The road pavement surface temperature is critical for assessing the potential for icing, and therefore requiring proactive deicing activities. Direct measurement of the surface temperature within +/- 0.2°C is possible using surface sensors embedded in the pavement surface. A 2005 study in Oklahoma City found that weather station skin temperatures are similar to bridge and approach temperatures within 2 degrees[24]. The best performance occurred when temperatures were below 2°C, and worst in dry conditions. Vendors claim surface moisture can be measured with 0.1-mm accuracy, and surface temperatures with 1-degree centigrade accuracy.

There are commercial software products that predict potential icing events with or without the additional use of a RWIS. These systems can also provide deicing protocol suggestions based on the forecast conditions. One such system is Roadcast™ by Meteorlogix. This system ingests weather forecast products from the National Weather Service (e.g. WRF, NAM, GFS) and uses vendor-added pavement thermal models to predict future pavement temperatures [25]. These systems are particularly useful for locations without RWIS, and may be unwarranted otherwise.

Hand held and vehicle-mounted instruments can also be used to measure surface temperature with infrared thermometers. Precaution must be made so that the vehicle exhaust does not interfere with the measurement. The relatively high labor cost of this technique make it unattractive.

The high traffic volume at airports has lead to the installation of RWIS systems at many airports. The typical cost of RWIS systems are $100,000 for a commercial airport, and are manufactured by Surface Systems, Inc. and ICELERT by Findlay Irvine [26]. A similar cost would be expected for the bridge.

In Canada, a survey conducted in 2000 showed that Canada has 138 RWIS towers in ten provinces and one territory [27]. Every agency indicated that embedded pavement sensors were incorporated into their systems, while only 5 indicated that video cameras were used for surveillance and precipitation detection. Thermal mapping is currently used by 3 of the responding agencies to monitor storm initiation and progression by almost every agency.

Because anti-icing is a proactive strategy, the timing of chemical application becomes the critical factor to ensure maximum safety and cost effectiveness. Chemicals applied too soon before the storm may require premature reapplication, resulting in higher costs. Conversely, the chemicals cannot be applied too late otherwise the compacted snow and ice layer may form, reducing road safety. Accurate and timely weather information, therefore, is extremely important for timing the application of chemicals. Whereas regional and provincial weather data is sufficient for travelers, anti-icing operations require more detailed weather information. Thermal mapping is another tool that can provide detailed information concerning the thermal properties of roadways, thus allowing the optimum placement of RWIS stations, as well as the development of heating and cooling models for problematic road segments to predict optimum chemical application times.

The New York City Department of Transportation (DOT) developed a fixed anti-icing system prototype for a portion of the Brooklyn Bridge. The flow chart of the anti-icing/deicing system operational sequence is shown in Figure 6. The system sprays an anti-icing chemical on the bridge deck when adverse weather conditions are observed. Anti-icing reduces the need to spread road salt, which has contributed to corrosion of bridge structures.

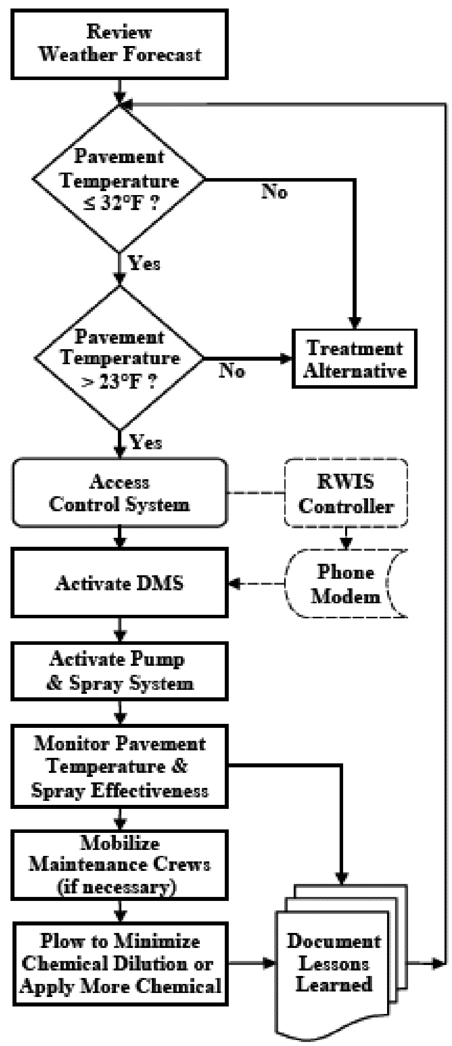

Figure 6: City of New York, NY Anti-icing/Deicing System Operational Sequence.

System Components: The anti-icing system is comprised of a control system, a chemical storage tank containing liquid potassium acetate, a pump, a network of PVC pipes installed in roadside barriers, check valves with an in-line filtration system, 50 barrier-mounted spray nozzles, and a Dynamic Message Sign

(DMS). The DMS displays warnings to alert motorists during spray operations. A Closed Circuit Television (CCTV) camera allows operators to visually monitor the anti-icing system.

Each self-cleaning nozzle delivers up to three gallons (11.4 liters) of chemical per minute at a 15-degree spray angle. This angle minimizes misting that could reduce visibility. Two nozzle configurations were implemented to investigate different spray characteristics. On both sides of one bridge section, nozzles were installed 20 feet (6.1 meters) apart for simultaneous spraying. On another section, sequential spray nozzles were mounted on only one side of the bridge.

In Europe, the term road weather information system (RWIS) is usually used to describe a system of sensors connected together to provide real time, accurate and site specific pavement surface conditions and weather data [23]. For anti-icing operations, it is critical to monitor the pavement temperature and presence of moisture on the road surface. However, RWIS stations can be configured to provide ambient (air) temperature, relative humidity, solar radiation, wind speed and direction, precipitation, and many other weather conditions. Individual RWIS sites are often referred to as remote processing unites (RPU's), consisting of several atmospheric sensors mounted to a tower, sensors embedded within and below the pavement surface, all connected to a data processing unit and communication equipment. A typical RPU is shown in Figure 7.

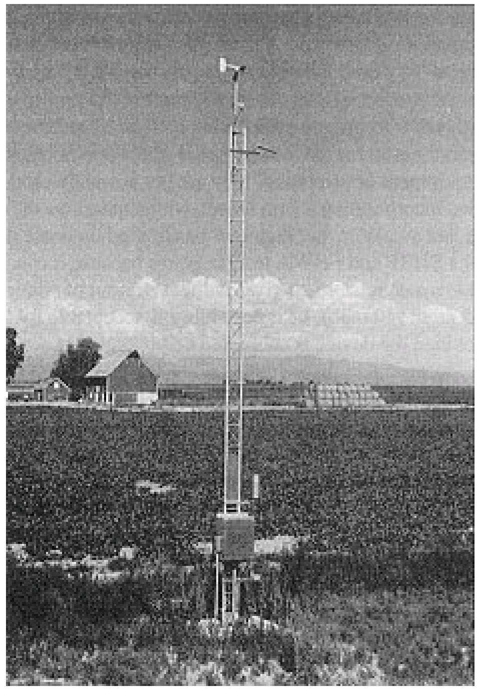

Figure 7: RWIS roadside installation [27].

European countries are moving quickly and with confidence to implement and expand the RWIS. In Fridbourg, Switzerland, there is one RWIS Remote Processing Unit (RPU) or remote weather station for every 3 to 4 km of freeway. Annual maintenance and operation costs run approximately $275 to $500 per station, depending on the number of sensors and detectors. Cameras are used in Sweden to detect the amount and the type of precipitation, and some can detect the presence of fog. This information is relayed to the traffic management center.

In terms of sensors, Switzerland uses Boschung's active/passive sensor system in some area. The Boschung system measures snow depth, wind speed and direction, relative humidity, dew point, air temperature, and freezing point of residual brine. This system provides a 2 ^{o}C warning before ice formation – typically about a ½- to 1-hr lead time, depending on the weather.

Thermal mapping is another important component in the RWIS. Thermal mapping of a road network consists of measuring pavement surface temperatures along all or part of a road network under varying atmospheric and solar conditions to determine pavement temperature differences, which can affect winter service strategies and tactics. The pavement surface temperature recording is conducted using hand-held or vehicle-mounted radiometers.

After the installation of the spreading device, accidents under winter road conditions decreased by more than 50 percent on this autobahn segment. The accidents involving minor injuries decreased by an even greater degree (85 percent). A cost-benefit ratio of 1.9 to 1 resulted, considering amortization of the 1.52 million DM (cost of construction and modification, in 1985 German Marks) over the 15-year estimated life of the system. The report recommends that this type of system is best suited to combat black ice and support conventional winter service where black ice or heavy snowfall is common.

If RWIS stations are equipped with active sensors that provide accurate real-time pavement conditions, then this is an important when unforeseen weather events occur. Technological developments in forecasting weather and in assessing pavement surface conditions now offer the potential for successfully implementing anti-icing treatments. Sensors embedded in the pavement surface are able to measure the temperature representative of the surrounding pavement and detect the presence of water or ice and a chemical freezing-point depressant. Signal information coming from these sensors has given maintenance managers the means to observe real-time pavement surface conditions; and when used with available algorithms, the information provides a reasonable prediction of pavement surface conditions for a period of up to 24 hours. Improved weather forecasting targeted specifically to local or regional road conditions also provides the maintenance manager with the means to predict pavement surface conditions. In addition, better communications rapidly relay this information to both maintenance forces and the public.

Porous Overlay:

A modified pavement surface to be used in conjunction with other deicing techniques has also been developed. The addition of a porous overlay comprised of aggregate and epoxy has the potential to store deicing chemicals that would otherwise drain or get splashed off by passing automobiles. SafeLane™ anti-icing pavement porous overlay, patented by Cargill Incorporation, uses a special aggregate that acts together with an adhesive, in a sponge-like manner such that when an anti-icing liquid is applied to the surface, it is retained for a significant portion of time (typically, many days) and remains effective as an anti-icing chemical during that time. The commercial SafeLane product has been installed at over 24 sites since 2003 [28]. Anecdotal evidence and company literature indicate that SafeLane has decreased accident rates and also decreased road maintenance costs at most installations. Maintenance costs are reduced because deicing chemicals can be applied during regular working hours instead of a on-call basis. SafeLane has replaced a problematic FAST system on Mitchell Bridge in Hibbing, Minn [28].

Snow Fence:

Blowing and drifting snow constitutes a major winter hazard in Anchorage. The mitigation of this hazard may be managed with storage-type and innovative snow fence technology.

The use of storage-type snow fences, i.e., fences that encourage the deposition of the snow in the lee of the fence by decelerating the airflow, is a common practice in Japan [9]. Improvements in visibility are realized by decreasing the amount of snow in transport downwind of the fence. Although it depends on terrain, fence geometry, and aerodynamics in the vicinity of the snow fence, most storage snow fences will become full during the winter season and will remain full until spring melting.

Heat Transfer Enhancement Using Nanofluids:

In the last decade, as energy costs have escalated rapidly, there is a need for new kinds of heat transfer fluids that will increase the thermal efficiency of any system and thus reduce overall energy consumption. Nanofluids have attracted attention as a new generation of engineered fluids for various heat transfer applications because of their excellent thermal performance described by Eastman et al. [29]. Nanofluids are the dispersions of nanometer sized particles (<100 nm) in a base fluid such as water, ethylene glycol or propylene glycol. Xuan and Li [30] had shown experimentally that the use of high thermal conductivity metallic nanoparticles (e.g., copper, aluminum, silicon) has the effect of increasing the thermal conductivity of such mixtures, thus enhancing their overall energy transport capability. Eastman et al. showed an increase of 40% in thermal conductivity with 0.3% (vol.) of copper nanoparticles in ethylene glycol.

In cold climates like those found in Alaska, heat transfer fluids encounter low temperatures. The commonly used heat transfer fluid in cold climate is ethylene glycol and water mixture. This mixture's thermal performance could be enhanced by adding nanoparticles. Kulkarni and Das [31] have measured the convective heat transfer coefficient of ethylene glycol and water with copper oxide (CuO), aluminum oxide (Al_2O_3) and silicon dioxide (SiO_2) nanoparticles. The results are shown below in Figure 8.

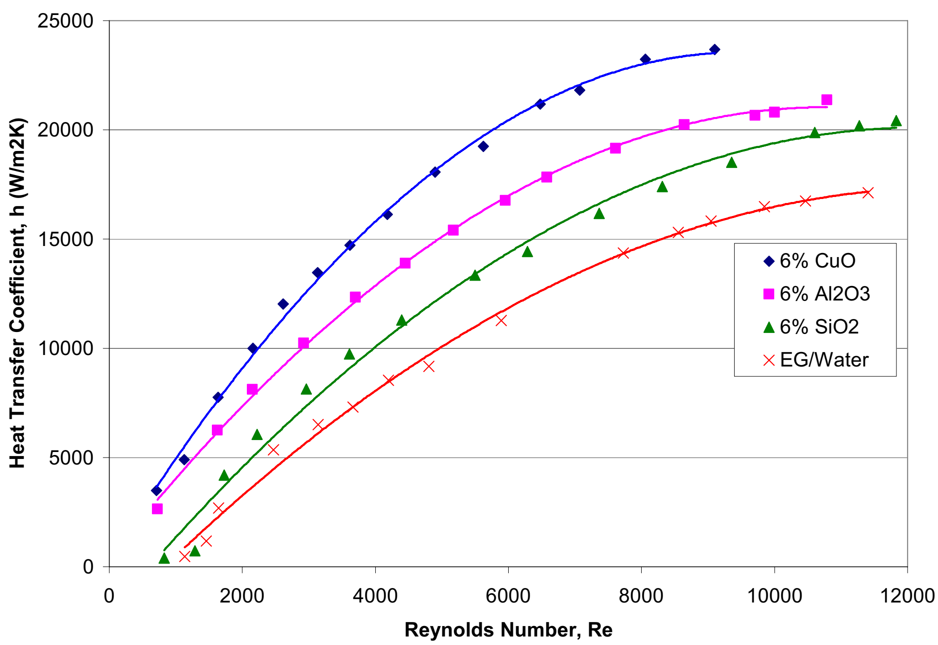

Figure 8: Comparison of heat transfer coefficient of various nanofluids with respect to glycol/water mixture.

From the above figure one observes that at a flow Reynolds number of about 5000, the heat transfer coefficient for a conventional glycol /water mixture is 10,000 W/m^2K. Whereas at the same Reynolds number the convection coefficient increases to about 18,000 W/m^2K for a nanofluid with 6 % by volume of CuO nanoparticles in the same glycol /water mixture.

Therefore, using nanofluids as the hydronic fluid for deicing and anti-icing is promising and warrants further investigation. A detailed analytical and numerical heat transfer analysis in the loops of the bridge deck heating system should be undertaken to determine the thermal efficiency enhancement and the resulting cost savings accurately.

5. GEOGRAPHIC, ENVIORMENTAL, AND OPERATIONAL INFORMATION OF THE BRIDGE

5.1 Geographic and Climatic Conditions

A field trip to Anchorage was made on January 3rd, 2007 to collect the geographic information of the bridge site. The east abutment, Anchorage Port, and the west abutment, Mat-Su Port, are shown in Figures 9 and 10, respectively.

At this preliminary point in the assessment of different anti-icing and deicing technologies, only a rough approximation for the number of "icing events" per year is necessary. Therefore, the potential effect of traffic volume will not be considered at this point, although its incorporation at a future time will be accommodated. A potential icing event is therefore defined as a period of time when the National Weather Service is reporting some degree of precipitation, and the ambient temperature is 32^{o}F or colder. During continuous precipitation, automated systems may activate on an average of approximately once per hour. Therefore, any hour may be a potential icing event, with a maximum of 24 icing events per day. This estimate can be considered an upper limit since the actual degree of precipitation at the bridge may not be significant enough to merit anti-icing activity. Also, if the temperature is significantly below the freezing point, anti-icing may not be necessary since the snow (the likely precipitation at cold temperatures) may easily be blown off the bridge and not pose an icing hazard.

The source of meteorological data is the NOAA National Climate Data Center, who maintains an archive of National Weather Service reported conditions for several locations in the Anchorage area (Figure 11). For this estimate, the hourly conditions at the Anchorage International Airport (Ted Stevens Airport) were used for the past nine winter seasons from Sept. 1, 1997 to April 1, 2006. Reported weather conditions that are flagged as a potential icing event range from intermittent rain or snow to continuous or heavy snow. Figure 11 shows a histogram of the events for all nine years. The average yearly number of events is 418, or a cumulative 17.5 days of potentially freezing precipitation. This is likely an upper estimate of the number of potential icing events. Because of the variability in weather conditions around the Anchorage area, particularly near the proposed Knik Arm Bridge, installation of a RWIS is greatly encouraged. A RWIS would provide more accurate local conditions and probably trigger anti-icing activity less frequently than this rough estimate.

Figure 9: View of the Port MacKenzie area

Figure 10: View of the Port of Anchorage area

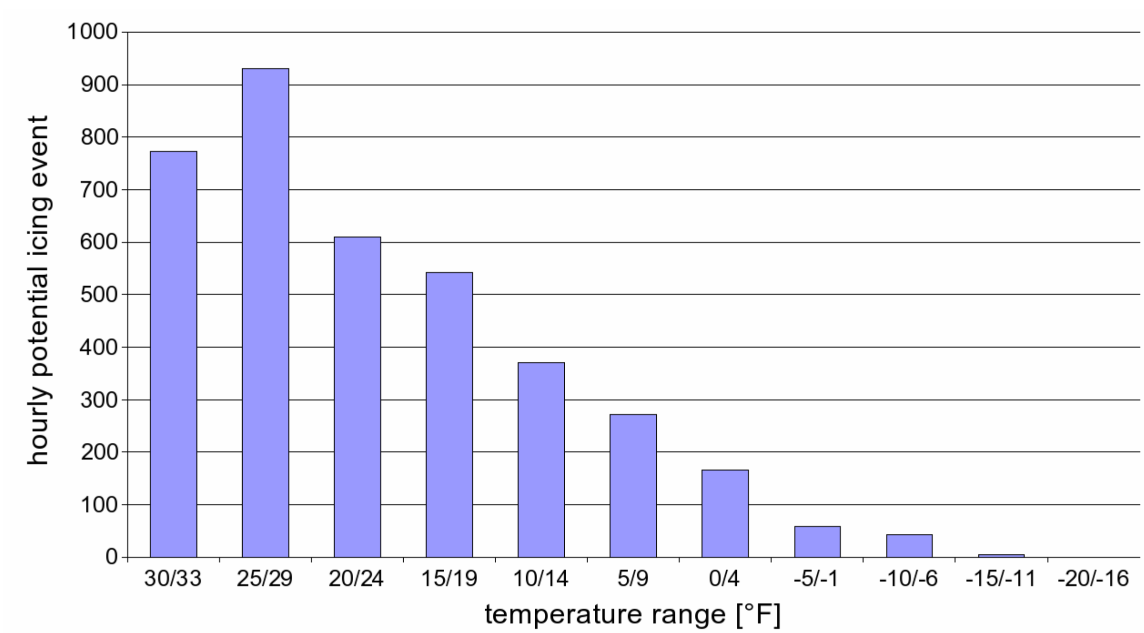

Figure 11: Potential icing event as a function of temperature.

5.2 Operational Information

Maintenance effort will vary with climatic conditions. A factor of great importance is pavement temperature. Pavement temperature directly influences the formation, development, and breaking of a bond between fallen or compacted precipitation and the road surface as well as the effectiveness of chemical treatments. It is also important when high humidity levels are accompanied by low dew point temperatures. Under these conditions there will be a greater potential for formation of frost and black ice. Unless some external source of heat is provided, the pavement temperature will generally track air temperature with a time delay. For road sections without obstructions to a clear sky view, solar radiation during the day and exposure to the clear night sky will affect the road surface temperature to a greater extent than on sections influenced by air contact only.

The use of an anti-icing technology such as FAST or the more conventional plow-truck distributors requires an estimate of the number of times the system must be implemented. The major factors that must be considered are: the rate of precipitation (if any), the temperature, and the rate of traffic flow. Higher precipitation rates require more anti-icing, and perhaps eventually if ice does begin to form, deicing. The temperature effects the rate of solid-liquid transition, which includes both the melting of snow or sleet on a warmer surface, and the solidification of melt water into ice. Temperatures just slightly below freezing (32^{o}F) are usually the most problematic. Once the temperature is significantly below the freezing point, the rate of melt is decreased, and traffic volume becomes significant. The instantaneous contact temperature between a vehicle tire and the road surface can be several degrees warmer than ambient, causing snow or ice on a frozen surface to quickly melt and refreeze, a process which can lead to black ice. Higher traffic volumes therefore may require more anti-icing activity.

A major safety issue of the Knik Arm Bridge during winter weather is when moisture freezes on bridge decks before the adjoining road, catching motorists off guard. Black ice forms when moisture condenses on a road or bridge and freezes, forming a thin, shiny and usually slick surface. Freezing of pavement moisture occurs often on bridges because cold air passing above and below it increases the rate of heat loss and promotes freezing. Bridges spanning open water are more prone to black ice formation. Black ice is often difficult for motorists to discern. Light-colored concrete bridges have a higher-thermal mass and tend to warm up and cool down more slowly than nearby pavement.

Other important climatic factors are type and rate of precipitation. Together with pavement temperature, they are the most important variables to consider when performing anti-icing operations. The operational guidance described later in this manual is presented in terms of these variables.

The Knik Arm Crossing Essential Fish Habitat Assessment of the Proposed Action reports that high-circulation rates in Knik Arm would dilute and dissipate any localized deicing chemical runoff and not impact any essential fish habitat.

6. RANKING AND FUTURE WORK

6.1 Ranking

Sections 3, 4 and 5 compose a comprehensive international literature investigation of de-icing and anti-icing techniques. In this Section, potential methods are ranked based on their cost and effectiveness and in terms of their suitability. Selection of the appropriate methods is also based on a number of factors specific to geographic areas and agency specifications. A comparison of these potential anti-icing/deicing methods is given in Table 4 below.

Table 4: Comparison of Various Anti-icing/Deicing Methods

Methods	**Capital Cost**	**Operation Cost**	**Effectiveness**	**Recommendation**
Chemical without FAST	*	*/**	**/***	***
Chemical with FAST	**	*	***	***
Thermal using hot fluid	***	**/***	**/***	**/***

Note: * – Low; ** – Moderate; *** – High

Based on the literature data in similar latitude, duration and intensity of freezing, and the fact that the thermal method may reduce the use of chemical agents substantially, *a combination of the chemical method with a Fixed Automatic Spray Technology and the thermal method* is suggested to be the best approach based on the cost-effectiveness criteria. For anti-icing and deicing chemicals, salt (NaCl) mixed with calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$) should be given high priority due to their excellent low-temperature applicability and extremely low cost (See Table 2). Fixed Automatic Spray Technology (FAST) along with a Road Weather Information System (RWIS) may be expensive for their capital cost, but their effectiveness in reducing the accident rate may make them economically viable method in the long term.

6.2 Future Work

Although this report provides a comprehensive international literature review on various anti-icing techniques, several hurdles standing in the way of successful implementation of anti-icing need to be further investigated and overcome. For example, the use of chemicals in solid form for anti-icing treatments demands precise timing of the application to minimize loss from traffic action. The use of prewetted salt can reduce loss during application due to particles bouncing off the pavement; prewetted salt may also be effective in reducing the amount of material that is blown off the road by traffic. In addition, the influence of the time between an application of salt and the onset of freezing precipitation is not fully understood.

Additional winter testing and evaluation of anti-icing technology should be conducted in the Knik Arm Bridge site to supplement the knowledge gained from literature information. Anti-icing operation tests should be conducted using chemicals under a variety of winter storm and traffic conditions. The role of traffic volume in these anti-icing operations needs to be assessed.

It is also strongly recommended to setup a weather station at the Bridge site to measure barometric pressure, temperature, humidity, rainfall, wind speed and direction. These data will provide first-hand weather information for decision making on anti-icing and deicing practice.

With these considerations in mind, *the focus of Phase 2 of this project is to identify several of the most promising candidate systems from Phase 1 for a detailed study for implementation*, including developing refined estimates of site-specific

- Storage, power, delivery system, etc. requirements
- Probabilistic economic analysis of the annual cost of the candidate system using
    - Statistical parameters of the number of freezing events per freezing season based on historical records.
    - Statistical parameters of the duration of individual freezing events in a freezing season based on historical records.
    - A planning horizon of a 50-year life with inflation-adjusted life-cycle costs for each type of system.

APPENDIX I: SELECTED CHEMICALS AND THEIR PROPERTIES

Table I.1: Various weather events* at the temperatures below -10 to -7°C (15 to 20°F) [3]

WEATHER ENVENT*	INITIAL OPERATION				SUBSEQUENT OPERATIONS			COMMENTS
	pavement surface at time of	maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		
	initial operation		liquid	solid or prewetted solid		liquid	solid or prewetted solid	
LIGHT SNOW STORM	Dry, wet, slush, or light snow cover	Apply prewetted solid chemical		55 (200)	Plow as needed; reapply prewetted solid chemical when needed		55 (200)	If sufficient moisture is present, solid chemical without prewetting can be applied
MODERATE OR HEAVY SNOW	Dry, wet, slush, or light snow cover	Apply prewetted solid chemical		55 (200)	Plow accumulation and reapply prewetted solid chemical as needed		70 (250)	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 140 kg/lane-km (500 lb/lane-mi) to accommodate longer operational cycles
FROST OR BLACK ICE	Any level	Apply prewetted solid		36-55 (130-200)	Reapply prewetted solid		36-55 (130-200)	1) Monitor pavement closely; if thin ice forms, reapply chemical at higher

		chemical			chemical when needed			indicated rate
FREEZING RAIN STORM		Apply prewetted solid chemical		70-110 (250-400)	Reapply prewetted solid chemical as needed		70-110 (250-400	1) Monitor precipitation closely 2) Increase spread rate toward *higher indicated rate* with increase in intensity of freezing rainfall; 3) Decrease spread rate toward *lower indicated rate* with decrease in intensity of freezing rainfall
SLEET STORM		Apply prewetted solid chemical		70-110 (250-400)	Plow as needed, reapply prewetted solid chemical when needed		70-110 (250-400)	1) Monitor precipitation closely 2) Increase spread rate toward *higher indicated rate* with decrease in pavement temperature or increase in sleet intensity 3) Decrease spread rate toward *lower indicated rate* with increase in pavement temperature or decrease in sleet intensity

Table I.2: Various weather events* at the temperatures below -10^{o}C (15 ^{o}F) [3]

WEATHER ENVENT*	INITIAL OPERATION				SUBSEQUENT OPERATIONS			COMMENTS
	pavement surface at time of	**maintenance action**	**dry chemical spread rate, kg/lane-km (lb/lane-mi)**		**maintenance action**	**dry chemical spread rate, kg/lane-km (lb/lane-mi)**		
	initial operation		**liquid**	**solid or prewetted solid**		**liquid**	**solid or prewetted solid**	
LIGHT SNOW STORM	Dry or light snow cover	Plow as needed			Plow as needed			1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction
MODERATE OR HEAVY SNOW	Dry or light snow cover	Plow as needed			Plow as needed			1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction
FROST OR BLACK ICE	Any level	Apply abrasives			Apply abrasives as needed			It is not recommended that chemicals be applied in this temperature range
FREEZING RAIN STORM		Apply abrasives			Apply abrasives as needed			It is not recommended that chemicals be applied in this temperature range
SLEET STORM		Plow as needed			Plow as needed			1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction

*GLOSSARY OF TERMS

Dry chemical spread rate. The chemical application rate. For solid applications it is simply the weight of the chemical applied per lane kilometer (or mile). For liquid applications it is the weight of the dry chemical in solution applied per lane kilometer (or mile).

Freezing rain. Supercooled droplets of liquid precipitation falling on a surface whose temperature is below or slightly above freezing, resulting in a hard, slick, generally thick coating of ice commonly called glaze or clear ice. Non-supercooled raindrops falling on a surface whose temperature is well below freezing will also result in glaze.

Frost. Also called hoarfrost. Ice crystals in the form of scales, needles, feathers or fans deposited on surfaces cooled by radiation or by other processes. The deposit may be composed of drops of dew frozen after deposition and of ice formed directly from water vapor at a temperature below $0^{o}C$ ($32^{o}F$) (sublimation).

Light snow. Snow falling at the rate of less than 12 mm (1/2 in) per hour; visibility is not affected adversely.

Liquid chemical. A chemical solution; the weight of the dry chemical in solution applied per lane kilometer (or mile) is the chemical application rate – the "dry chemical spread rate" – used in this appendix.

Moderate or heavy snow. Snow falling at a rate of 12 mm (1/2 in) per hour or greater; visibility may be reduced.

Sleet. A mixture of rain and of snow which has been partially melted by falling through an atmosphere with a temperature slightly above freezing.

APPENDIX II: FIXED, AUTOMATIC SPRAY TECHNOLOGY (FAST) SYSTEMS IN USE

Table II: FAST systems in use in 2000 (available at http://www.sicop.net)

State	Start-up	company	location	Nozzle	sensor	chemical
Colorado	1998	Odin	5 bridges	flush		KA
Colorado	1998	Odin	bridge/RR x'ing	flush	active	KA
Kansas		Odin		flush		CMA
Kentucky	1997	Odin	I-75, exit 29A	parapet	passive	CaCl
Maryland	1999	Odin/SSI	I-68	flush		CMAK
Michigan		Odin	Rt. 31	parapet		MgCl
Michigan		Odin	steep hill	curb		Dow armor
Michigan		Odin	Rt. 131	flush		KA
Minnesota	1995	Odin	Rt. 169	flush		brine, CaCl, KA
Minnesota	1998	Odin	I-35	flush		KA
Minnesota	1999	Boschung	I-35W	barrier/flush	passive	KA
Minnesota	1999	Odin	Rt. 61	flush	passive	KA
Nebraska	1999	Odin	I-80	curb/flush	active	IceBan, MgCl
New York		NYCDPW	Brooklyn brdg.	flush	active	
North Carolina	1998	Odin	Rt. 105			CMA
Pennsylvania	1999	Boschung				MgCl/CaCl
Pennsylvania	1999	Boschung				MgCl/CaCl
Pennsylvania	1999	Boschung				MgCl/CaCl
Utah	1996	W/AEL	I-215			NaCl/MgCl
Virginia	1998	Boschung	I-66 ramp			MgCl
Virginia	1999	Boschung	Blue rdg. pkwy			KA
Wisconsin		Boschung	I-43	flush	active	MgCl
Wisconsin	2000	Nu-metrics	Hwy. 50	flush	active	MgCl

APPENDIX III: CASE STUDY: HYDRONIC HEATING OF BRIDGE DECK VIA HOT FLUID

Heating walkway at various places for deicing and anti-icing by circulating hot fluid is not common. Where waste heat is available from industrial plants this application can be successful. In some university campuses, where their power plants produce waste heat, this principle has been exploited. Tubes carry hot fluid and circulate it under the concrete walkway or pavement. The slab is usually insulated under the tubes to direct the heat upwards towards the snow and ice.

Following a similar assumption taken by Yehia and Tuan [1], it is assumed that the heating will automatically go into active mode as the snowfall causes an ice build up or frost and black ice form on the bridge deck. The heating gets activated before the ice thickness builds up beyond 1/8 inch.

Therefore the volume of ice to melt at one occurrence = (1/8inch × 24 feet × 2 miles) = (0.003175m × 7.315m × 3218.694m) = 74.75 m^3. Here we have used 3 lanes each 8 ft wide and a bridge length of 2 miles.

$$Latent\ heat of\ melting\ ice = 334\,kJ/kg$$

$$\rho_{ice} = 917\,kg/m^3$$

$$q_{total} = 74.75\,m^3 \times 917\,kg/m^3 \times 334\,kJ/kg = 228.94 \times 10^5\ kJ$$

Assuming a 20% heat loss to the environment due to convection and radiation, total heat required to melt the ice is

$$q_{total} = 274.73 \times 10^5\ kJ$$

It has been analyzed the weather data of Anchorage to estimate the occurrence of 400 events of snow, frost and ice per year for the Knik Arm Bridge.

$$q_{year} = 274.73 \times 10^5 \times 400\,kJ = 109{,}892 \times 10^5\ kJ/Yr$$

Number 2 fuel oil heating value

$=136{,}000\,Btu/gal(1\,kJ/0.94782\,Btu) = 143{,}487\,kJ/gal$

Assuming a furnace efficiency η = 0.9:

$$q_{fuel} = \frac{274.73 \times 10^5 \times 400}{0.9} = 122{,}102.222 \times 10^5\ KJ/Yr$$

Fuel in gallons required per year is:

$$q_{fuel} = 122{,}102.222 \times 10^5\ KJ / Yr\,(1\,gal / 143{,}487\,KJ) = 85{,}096\,gal / Yr$$

Annual cost of fuel consumed:

$$Cost_{fuel} = 85{,}096\,gal / Yr\,(\$2.30 / gal) = \$195{,}722 / Yr$$

Fuel cost per m^2 of bridge deck area is \$195,722/(7.315)(3218.69) = \$8.3/ m^2

APPENDIX IV: CASE STUDY: HEATING LOOP DESIGN

The design adopted here is similar to the system prepared by Spitler and Ramamoorthy [13] for bridge deck deicing in Oklahoma on I-40 using geothermal energy by heat pumps.

The energy required to melt

$$(1/8inch \times 24\,feet \times 2\,miles) \text{ of ice} = 274.73 \times 10^5\ kJ$$

Assume 400 heating loops like the one shown below in Fig. 1 for the whole 2 miles span.

Each loop is about 8 m (24 feet) long. This design circumvents the need for big diameter piping at the beginning and small diameter at the end of the heating loop on a long bridge.

Therefore heat required per loop

$$q_{1loop} = \frac{274.73 \times 10^5}{400} = 68682\,kJ / Loop$$

From the transient heat conduction analysis of Yehia and Tuan [13] it was observed that for a 6-inch thick concrete deck it would take about 30 minutes to start melting the ice.

$$q_{1loop/event} = \frac{68682}{1800s} = 38.16\,kW$$

The shape factor equation for the geometry shown in Figure 12 below from White (1984) is:

$$q = Sk(\Delta T)$$

where S is the shape function and ΔT is the temperature difference between the top surface of the deck (usually ice) and the tube surface.

$$S = \frac{2\pi L}{\ln[b/r(0.637 - 1.781e^{-2.9a/b})]}$$

Use the thermal conductivity of high density concrete $k_{concrete} = 0.896W/mC$ and L is the length of the tubing in a loop.

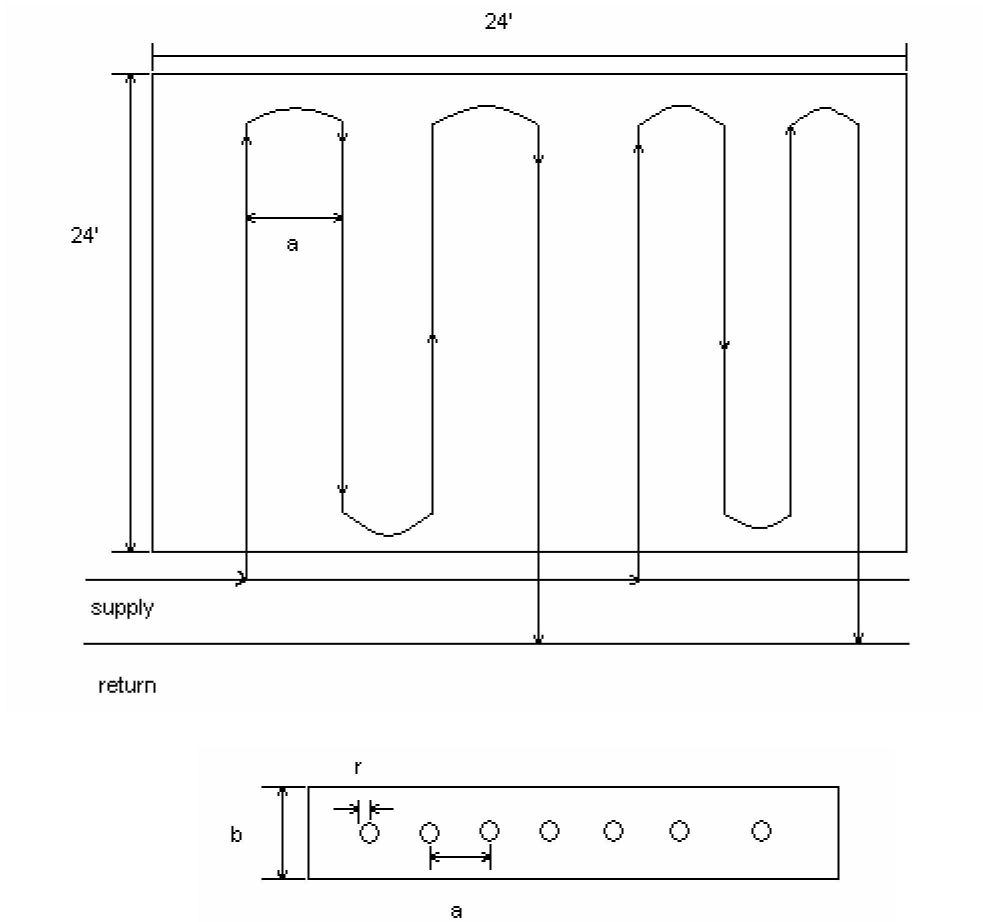

Figure 12: Plan view of the hydronic piping lay out on a section of the bridge deck (top). Cross sectional view of the bridge deck (bottom). Not shown is a layer of insulation below the tubes.

Following Yehia and Tuan we use a bridge deck thickness of b =0.1525 m (6 inches). We select a tube spacing a = 0.6096 m (2 feet) and a tube radius r = 0.025 m (1 inch).

For this design the tube length per loop comes out to be L =102.4 m/loop. Each loop has 13 straight pipes and 12 U-bends.

Therefore the shape function is

$$S = \frac{2\pi(102.4m)}{\ln[6''/1''(0.637 - 1.781e^{-2.9(2'/0.5')})]} = 479.88\,\text{m}$$

Therefore

$$\Delta T = \frac{q_{1loop/event}}{k_{concrete} \times S} = \frac{38.16\times10^3\,W}{0.896W/m.C \times 479.88\,m} = 88.75C$$

If we take the temperature of the ice surface to be 0°C the pipe surface temperature should be 88.75°C, which is a reasonable number.

One may design fluid temperature into the loop at 95°C and out of the loop at 85°C giving a mean temperature in the loop of 90°C.

Pipe size and pumping horsepower are calculated below.

Per loop

$\dot{m} c_p (\Delta T_f) = 38.16\, kW$; $\Delta T =$ Temperature difference of fluid between inlet and outlet in the loop is 10 C.

$\dot{m}(4.2\, KJ / kg \cdot K)(10) = 38.16;$

$\dot{m} = 0.91 kg / s$

$\rho A V = \dot{m}$

$(1000\, Kg / m^3)(\pi / 4)(0.051 m)^2 V = 0.91$

$V = 0.45\, m / s = 1.47\, ft / s$

A velocity of 1.47 ft/s is quite reasonable and will cause less pressure drop.

Head loss: $h_f = \dfrac{fLV^2}{2gd} = \dfrac{0.02(102.41)(0.45)^2}{2(9.81)(0.051)} = 0.4145\, m$

Pressure Drop: $\Delta P = \rho g h_f = 1000(9.81)(0.4145) = 4066\, Pa$

Pump Power: $\dot{W} = \dfrac{\dot{Q}\Delta p}{\eta_p} = \dfrac{9.1 x 10^{-4} (4066)}{0.8} = 4.62\, W$

Q is volumetric flow rate in a loop, assuming a pump efficiency of 80 %.

For 400 loops the total power = 400 loops (4.62) = 1850 W = 1.85 kW

1 hp = 745.7 W

1850 W = 2.48 hp. Double this size for valves and fittings in the line. Thus increase the pump size to 5 hp.

Energy per year for pumping: $(1.85\, kW)(2)(1\, hr / event)(400\, events / year) = 1480\, kWh / yr$

At \$0.10/Kwh, the annual cost to run pump is (\$148/yr).
Increase this by a factor of 10 for omitted consideration in the piping head loss and flow.
Therefore, the pumping cost is \$1500/yr.

Total flow in supply and return headers:

$= 400(9.1)(10^{-4}) = 0.364\, m^3 / s$

Velocity $\bar{v} = \dfrac{0.364}{(\pi / 4) d_2^{\,2}}$; where d_2 is diameter of header

In the header assume a reasonable velocity $\bar{v} \approx 15\, ft/s = 15(0.3048) = 4.572\, m/s$

$d_2^2 = \dfrac{0.364\, x\, 4}{4.572(\pi)}; d_2 = 0.318 m / 0.3048 = 1\, ft$

Use 12" diameter with reducers to 8",6",4" and finally to 2" diameter pipe at the end.

We have presented earlier in a table obtained from Yehia and Tuan the cost of hot water system per square meter of bridge deck as \$161/m^2.

Our approximate cost estimation comes close to this number for the Knik Arm bridge. The actual design will be based upon ethylene glycol and water mixture and not just water.

Please note that this is a quick approximate calculation due to the short period allocated to this study to arrive at approximate numbers. For an accurate assessment a transient heat conduction analysis of the bridge deck slab and a finer convective calculation of the heat transfer from the hydronic fluid in the tube is necessary to establish the design properly. If nanofluids are used, due to their higher efficiency the size of the system and the operating cost will be reduced.

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