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Final Report

The Aurora Consortium:

Laboratory and Field Studies of Pavement Temperature Sensors

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16. Abstract (Limit: 200 words)

The Aurora Consortium is a joint program of collaborative research, evaluation and deployment of advanced technologies for detailed road weather monitoring and forecasting. Members seek to implement advanced road and weather information systems that fully integrate state-of-the-art roadway and weather forecasting technologies.

Many agencies use various models of in-ground and mobile sensors to measure pavement temperature. However, little documentation exists on the accuracy of the various sensors, and there is no standard methodology for sensor testing. The data and conclusions drawn from this study are published so that Aurora members and others will have additional information to assist in their implementation and procurement decisions. Additionally, results from this study will be used by the NCHRP to develop testing and calibration standards for pavement sensors.

The objective of this project was to conduct both laboratory and field studies of various competing models of in-pavement (contact) and mobile (non-contact) type pavement temperature sensors and compare them to baseline readings in order to quantify the surface temperature measurement performance of each sensor and sensor type. The laboratory tests were conducted at the Braun Intertec laboratory in Bloomington, Minnesota. Field tests were conducted at the Minnesota Department of Transportation's (Mn/DOT's) Mn/ROAD facility near Monticello, Minnesota.

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The Aurora Consortium:
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Executive Summary

Project Overview

This report presents the methods, results and conclusions of the *Laboratory and Field Studies of Pavement Temperature Sensors* evaluation sponsored by the Aurora Consortium. The objective of this project was to conduct both laboratory and field studies to evaluate the pavement surface temperature reporting performance of various models of in-pavement (contact) and mobile (non-contact) pavement temperature sensors in varying environmental conditions.

Methodology Overview

Sensors Tested

Six in-pavement sensors were tested in this study:

- Aanderaa 3565 Road Condition Sensor
- Boschung America BOSO Passive
- LUFFT FASS Black Ice Detector IRS-21
- Point Six Wireless Point Probe
- SSI FP-2000
- Vaisala DRS 511

Two mobile sensors were also tested:

- Control Products 999J
- Sprague RoadWatch

All of the sensors were evaluated by comparing their reported temperature readings, at any given time, to the readings of closely-located, highly-accurate baseline thermistors that were affixed to the pavement surface.

Laboratory Tests

The laboratory tests were performed in a controlled climate test chamber to ensure that accurate, repeatable and reproducible results would be obtained. Two pavement test-sections (one asphalt and one concrete) served as test platforms for each test. The in-pavement sensors were installed in each of the two pavement test sections according to vendor specifications. Mobile sensors were mounted approximately four feet above each test section to simulate a vehicle mounted installation.

The surface temperature reporting performance of each sensor was evaluated with the following environmental tests: fixed and varying temperatures, with and without direct solar impact, snowfall, rainfall, frost and the application of sodium chloride solutions. Additionally, the mobile sensors were subjected to a series of tests to determine the effects of varying acclimation times, installation heights and air temperatures. A total of 15 sets of laboratory tests were conducted as part of this evaluation project.

Field Tests

The field tests were performed on temperature sensors installed in both concrete and asphalt portions of an existing low-volume test road to analyze sensor performance under "real world" conditions. The six in-pavement sensors were installed in the existing roadway, and the two mobile sensors were mounted to a test vehicle. A total of six sets of field tests were conducted.

Results Overview

Mean absolute error was the primary statistical measure used to present and compare sensor results.

In-Pavement Sensor Results

In the laboratory, the constant temperature tests yielded the most accurate results, with sensor readings averaging within 0.4° C (0.7° F) of the baseline temperature. During the various environmental factor tests, such as varying temperature, rain or snow, the average temperature error was 0.8° C (1.4° F). Much of the error associated with the varying environmental conditions resulted from in-pavement sensors reporting temperature change more slowly than the actual pavement surface temperature.

The field testing indicated that daily thermal cycles (solar heating or radiational cooling) can have a significant effect on sensor accuracy. Clear sky conditions during either day or night resulted in sensor errors, typically between 0.5 and 1.0° C (0.9 and 1.8° F). It was shown that cloud cover affects radiational cooling and the accuracy of the sensor. During clear sky conditions, some sensors reported the changing temperature at a different rate than the baseline pavement sensors.

Mobile Sensor Results

Overall, the mobile sensors reported similar levels of performance and accuracy to the in-pavement sensors. The average temperature error for the mobile sensors for the laboratory and field tests was 0.8° C (1.4° F).

The laboratory testing indicated that the mobile sensors were more accurate on concrete than on asphalt. The concrete average error was 0.3° C (0.55° F) compared to an asphalt average error of 0.7° C (1.26° F). The field testing suggested a similar trend.

Conclusions and Recommendations

Through a wide range of Aurora-approved laboratory and field test procedures, this study met its objective of evaluating the surface temperature reporting performance of various models of fixed and mobile pavement temperature sensors in varying environmental conditions.

The study results offer a detailed understanding of the range of accuracy that can be expected with these sensors. Development of an *acceptable* range of accuracy is one possible direction that the RWIS community may wish to further explore.

Other sensor performance characteristics, such as detection of surface moisture condition or freezing point, were not tested or evaluated as part of this study. It is recommended that these parameters be considered for a future study. A separate study conducted under the National Cooperative Highway Research Program (NCHRP) Project 6-15 includes development of testing methods for pavement surface conditions and chemical solution freezing point.

The following conclusions were drawn from the laboratory and field test results presented within the main body of this report:

General

- Throughout a variety of environmental conditions tested in both the laboratory and the field, on average, both the in-pavement and mobile sensors reported surface temperatures within 0.8° C (1.4° F) of the actual pavement surface temperature.

- Tests involving the application of sodium chloride to the sensors demonstrated that the effect of sodium chloride on sensor temperature reporting performance was insignificant.

In-Pavement Sensors

- Laboratory tests indicate the performance of in-pavement sensors was not significantly affected by pavement type.

- In the field tests, however, the in-pavement sensors installed in asphalt pavement were more accurate than the sensors installed in concrete.

- Field temperature tests indicate that in the "real world," the in-pavement sensors might not track ambient temperature fluctuations as well as in the laboratory.

Mobile Sensors

- In both laboratory and field tests, pavement type was shown to have a noticeable effect on mobile pavement sensor performance. The mobile sensors, on average, performed 0.5° C (0.9° F) more accurately in the tests on concrete.

- Additional field investigation of the mobile sensors is recommended to determine how varying pavement type and environmental conditions, such as snow, ice, wind and solar radiation, affect sensor performance.

This report presents and summarizes the results of the study for the reader, as a possible aid in determining which sensors are best suited for their needs. This report does not rank or judge the quality of sensors. Instead, it presents results that readers may use to choose the best sensor for their needs.

1 Introduction

This report presents the findings of the Aurora-sponsored *Laboratory and Field Studies of Pavement Temperature Sensors*. The objective of this study was to measure and compare the surface temperature reporting performance of various competing models of pavement temperature sensors in varying environmental conditions.

1.1 Background

The Aurora Consortium is a joint program of collaborative research, evaluation and deployment of advanced technologies for detailed road weather monitoring and forecasting. Members seek to implement advanced road and weather information systems that fully integrate state-of-the-art roadway and weather forecasting technologies.

Many agencies use various models of in-ground and mobile sensors to measure pavement temperature. However, little documentation exists on the accuracy of the various sensors, and there is no standard methodology for sensor testing. The data and conclusions drawn from this study are published so that Aurora members and others will have additional information to assist in their implementation and procurement decisions. Additionally, results from this study will be used by the NCHRP to develop testing and calibration standards for pavement sensors.

1.2 Project Overview

The objective of this project was to conduct both laboratory and field studies of various competing models of in-pavement (contact) and mobile (non-contact) type pavement temperature sensors and compare them to baseline readings in order to quantify the surface temperature measurement performance of each sensor and sensor type. The laboratory tests were conducted at the Braun Intertec laboratory in Bloomington, Minnesota. Field tests were conducted at the Minnesota Department of Transportation's (Mn/DOT's) Mn/ROAD facility near Monticello, Minnesota.

The scope of the project included:

- Conducting telephone interviews and/or e-mail surveys of Aurora members to determine their desires and requirements for the study.
- Conducting a literature search and contacting key experts from around the world to determine the state-of-the-practice for pavement sensor research.
- Soliciting vendors to participate in the study.
- Acquiring sensors from Aurora members and vendors.
- Preparing an Evaluation Test Plan.
- Comparing sensor readings in a controlled laboratory environment.
- Comparing sensor readings in an "operational" field environment.
- Comparing sensor readings under various temperature and weather conditions.
- Comparing the effects of commonly-used road anti-icing chemicals on sensor readings.
- Analyzing and managing data.
- Preparing a Draft Report.
- Soliciting comments from vendors and Aurora team.
- Preparing a Final Report and publishing it on the Aurora Consortium's website.

2 Methodology Overview

This section presents on overview of the methodology used in developing the tests. This section includes information about the literature search on pavement sensor testing, sensor procurement, data acquisition, baseline theory and statistical analyses.

2.1 Literature Search

A literature search was conducted to gather and summarize existing knowledge pertaining to pavement temperature accuracy and testing. The search used a combination of Internet search engines and the following transportation literature resources:

- National Transportation Library
- Transportation Research Board Database
- CalTrans PATH Database
- Mn/DOT Library

The majority of the pavement temperature test documents focused on the performance difference of sensors installed in different pavement types and at varying temperatures. The temperature sensors themselves were rarely evaluated. Although these tests were interesting, they generally did not describe lessons learned in conducting pavement temperature sensor evaluations.

There were two studies that should be noted for their applicability to the Aurora evaluation:

1. The Ohio Department of Transportation (ODOT) in conjunction with Ohio University conducted a study to evaluate the accuracy of ODOT Roadway/Weather Sensor Systems for Snow and Ice Removal Operations. This study focused on Road Weather Information System (RWIS) pavement sensors, which were tested under controlled conditions in a climate chamber. The scope of this test included temperature, chemical concentration and liquid depth measurement. The study was done in the summer of 2002 [4].
2. Ministère de l'Equipment des Transports et du Logement (METL) has developed a pavement sensor calibration methodology and testing procedure. This document describes in detail the test method and procedures that were used for calibrating and testing the accuracy of pavement temperature sensors under various conditions.

See Appendix A for references to these and other studies related to pavement sensor testing.

2.2 Sensor Procurement

Pavement temperature sensors were procured using the following process:

1. Aurora members were polled for instruments that they were are able to provide for the test.

2. Vendors were solicited, by open invitation, to participate in the testing program by providing their sensors for the test. Follow-up contact was required to secure a reasonable number of sensors.

3. Any vendors that were not selected for testing and wished to have their sensors included in the test or separately tested were allowed to submit a request. If approved by Mn/DOT, these additional sensors would have been included in the test, with the vendor paying the additional cost.

The evaluation team worked closely with vendors to ensure that the subject sensors were correctly installed and calibrated. In addition, vendors were invited to inspect and comment on all test activities. The following list summarizes vendor involvement in the project:

1. Vendors were offered an opportunity to visit the laboratory and field environments during sensor installation and testing.

2. Vendors were provided an opportunity to review and comment on raw test data prior to the publication of findings.

3. Vendors were offered an opportunity to review and comment on the Draft Report prior to publication.

The Aurora Consortium made the final determination of the various sensors to be tested. Table 1 provides the list of vendors that participated in the evaluation.

Table 1. Participating Vendors

In-Pavement Sensors	**Model**
Aanderaa	3565 Road Condition Sensor
Boschung America	BOSO Passive
LUFFT FASS Black Ice Detector	IRS-21
Point Six – Weather Safety Solutions	Wireless Point Probe
SSI (Quixote Corporation)	FP-2000
Vaisala	DRS 511
Mobile Sensors	
Control Products	999J
Sprague	RoadWatch

2.3 Data Acquisition Systems

The intent of this project was to conduct tests so that the test conditions mimicked an actual deployment as much as possible. To this end, manufacturer-supplied sensors and related data collection equipment were used. For example, most subject sensors include a Remote

Processing Unit (RPU) that captures and processes the raw sensor signals. All tests in this project were conducted with the manufacturer's RPU and any other proprietary data collection devices. This approach paralleled an actual field deployment, but restricted data collection options to only what the manufacturer makes available. For example, many RWIS sites use the Environmental Sensor Stations (ESS) protocol of the National Transportation Commissions for Intelligent Transportation Systems Protocol (NTCIP) standards. NTCIP Object Definitions for ESS Joint NTCIP Committee Standard 1204 require that the current pavement surface temperature be reported in tenths of degrees Celsius.

For the laboratory and field testing, the individual subject and baseline sensors (except the Point Six sensor which transmits data to its RPU via radio signal) were wired directly to their respective RPUs. In the laboratory, RPUs were directly connected to one of seven laboratory data acquisition computers. When moved to the field, the RPUs were installed in a roadside cabinet next to the test area. The field RPUs were then connected to seven field office data acquisition computers via a serial communications server and Ethernet network.

Whenever possible, data output from the manufacturer's system was collected according to the following criteria:

- Baseline temperature data was collected at least to the nearest 0.01° C.
- Subject temperature data was collected at least to the nearest 0.1° C (except Sprague sensor data resolution was to the nearest 0.55 ° C).
- Data was automatically collected once every two minutes or less.
- Vaisala sensor data was collected every 10 minutes due to the sensor's RPU data storage limitations.
- All incoming data included a time stamp.

Figure 1 provides an overview of the data acquisition system components deployed in the field. This figure indicates which operating system each computer ran. Operating systems were selected to accommodate the vendors' software.

Figure 2 shows the data collection hardware at the controlled climate laboratory. The seven computers used for data collection are on the right side of the photo and the test chamber door is located to the left of the computers.

2.4 Baseline Methodology

The baseline, in theory, represents the exact value of the experimental variable (temperature). The baseline for each subject sensor was determined using data from a nearby, specifically calibrated, baseline thermistor affixed to the pavement surface. The accuracy of each subject sensor was then determined by comparing its temperature output, at any given time, to the temperature output of the corresponding baseline thermistor.

Figure 1
Data Acquisition System Schematic for Field Tests

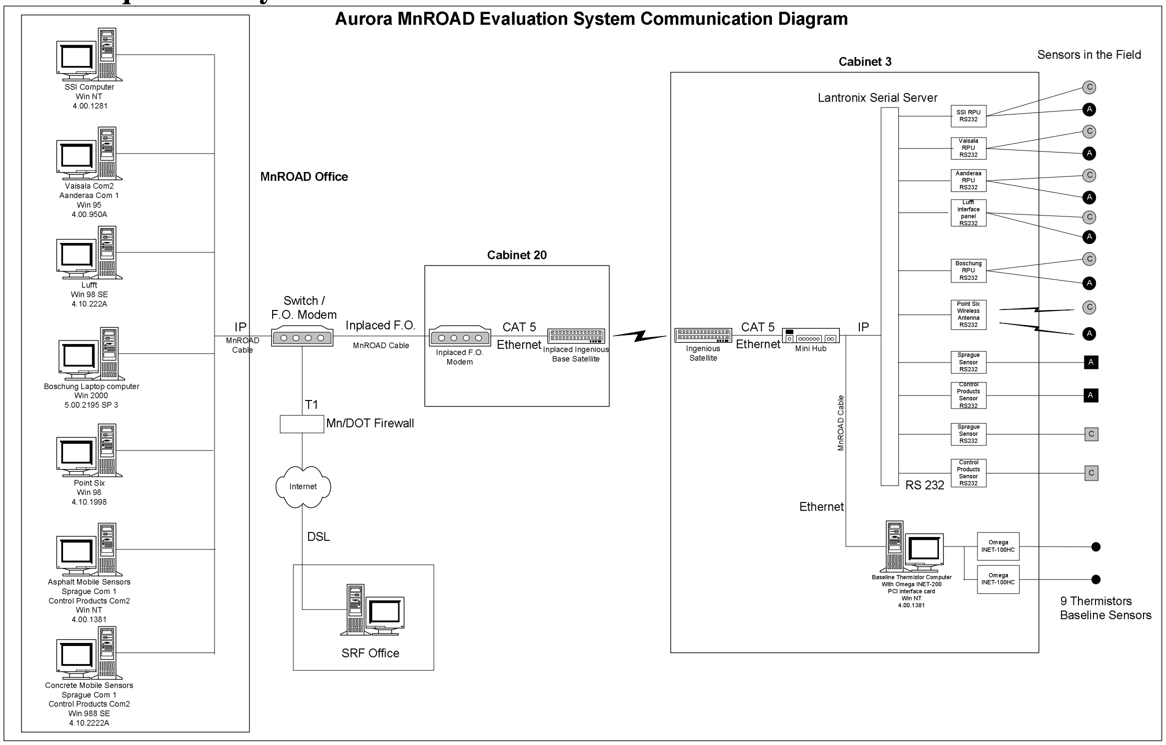


Figure 2
Data Acquisition System at the Laboratory

The pavement sensors were compared with the baseline sensor that was closest to each sensor because there is some spatial temperature variability in on the surface of the slab. Because the cooling fans were located in the upper back of the room and pushed air towards the front of the room, all points on the surface of the slab did not maintain exactly the same temperature. While comparing closely situated sensors and baselines, both the baselines and sensors had reached stable temperatures. For the baselines, which were affixed to the surface of the pavement, stability occurred when the pavement's surface had become stabilized.

The baseline data for both the laboratory and field portions of the evaluation was produced from calibrated thermistors capable of measuring temperatures to an accuracy of 0.10° C at 0° C (0.18° F at 32° F). The baseline sensor system's accuracy was stable over a temperature range of 0° C to 70° C (32° F to 158° F). As the measurement temperature proceeded below 0° C (32° F) this accuracy was 0.18° C at –20° C (0.32° F at –2° F) and 0.25° C at –40° C (0.45° F at –40° F).

2.4.1 Baseline Equipment

Thermistor-based sensors were selected over technologies such as Resistance Temperature Detectors (RTDs) or thermocouples. This decision was based on accuracy, temperature range, instrumentation availability, package design and cost. Omega was selected as the source for most of the baseline equipment to minimize system integration complexities. Yellow Springs Instruments (YSI) was selected for the thermistor elements because they are Omega's supplier (aiding in system integration) and they offered superior selection and service for this important element.

The Omega InstruNet Series, Direct Sensor Data Acquisition System, was selected. It is a PC-based system using a PCI data acquisition card capable of controlling 16 interface boxes. Each interface box was capable of eight sensor inputs. One advantage of the InstruNet system was that the interface boxes could monitor thermistors, RTDs, or thermocouples, providing cost-effective flexibility if the need arose.

Table 2 provides a breakdown of the baseline system components used for this project. Technical sheets and specifications are presented in Appendix B.

Table 2
Baseline System Components

Vendor	Part	Description	Qty
Omega	INET 200	PCI data acquisition card	1
Omega	INET 100HC	Sensor interface box	3
Omega	INET 311-5	Power supply	1
Omega	INET 300	Network power adaptor	1
Omega	OT 201-16	Thermo-conductive paste	1
Omega	OB 400	Thermo-conductive cement	1
Omega	OMX-R4.7K	Precision Shunt	24
YSI	YSI-081-55033-NA-FP-480ST	Thermistor (calibrated at 0° C)	20
YSI	YSI-081-55033-NA-FP-480ST	Thermistor (calibrated at –40°, 0° & 25° C)	4

The Yellow Springs Instruments YSI-081-55033-NA-FP-480ST thermistor was selected due to its small thermal mass and its maximum interchangeability error of ±0.10° C over 0° C to +70° C temperature range (±0.18° F over 32° F to +158° F). This thermistor was a nominal 2252-ohm thermistor with 480-inch vinyl cable leads and was packaged in a 3/8 diameter by 1/8 high stainless steel package. The 55xxx series probes were glass encapsulated providing a hermetic seal. YSI also calibrated each thermistor, minimizing interchangeability variations in the baseline data.

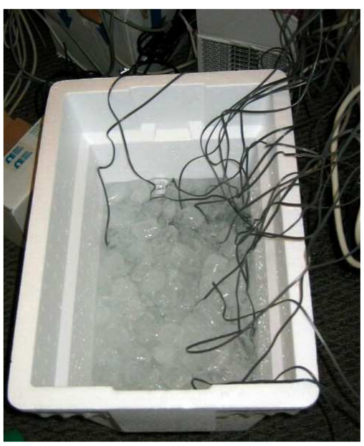
Omega OB 400 thermal conductive cement was used to maximize thermal conductivity between the thermistors and pavement test sections.

The Omega INET 200 data acquisition card spooled the baseline sensor data, by channel, into a spreadsheet format for analysis.

2.4.2 Thermistor Testing

The baseline sensors were ground-truthed at the SRF Consulting Group laboratory on August 11, 2003, by placing them in an ice bath. All 24 baseline thermistors were placed in a Styrofoam cooler containing a mixture of ice and chilled distilled water. The ice bath (shown in Figure 3) was stirred for several minutes prior to and during data collection to allow the temperature to stabilize. The data collection software was configured to collect data every minute for five minutes.

Figure 3
Thermistor Ice-Bath Testing



The expected thermistor performance was ± 0.10˚ C over a temperature range of 0˚ C to 70˚ C. Baseline testing in the ice bath revealed that 23 of the 24 thermistors met this requirement. The average error of these 23 sensors was -0.00014˚ C. This average error is the difference between the sensor readings and the ice bath temperature (the ice bath temperature was presumed to be 0.00˚ C).

An informal test at room temperature was also conducted by allowing all of the thermistors to stabilize in water overnight. Data was then collected every minute for five minutes.

The one thermistor (serial number 016) that did not meet the manufacturer's specified temperature accuracy reported higher temperatures in the ice bath test (0.17˚ C) and in the room temperature test (approximately 0.2˚ C higher). This sensor was not used in the testing.

2.4.3 Baseline Bench Test

Prior to commencing with the subject test plan, verification of the baseline procedure was performed through bench testing at SRF's laboratory. This verification was performed to verify the data collection procedures and provide confidence in the measurement systems operation and accuracy.

Additionally, another test was conducted to evaluate different options for attaching the thermistors to the pavement. The attachment options included affixing the baseline sensor to the surface of the pavement or placing the sensor in a ¼-inch deep hole, which would be dug into the pavement. Thermal conductivity between the sensor and pavement was accomplished through the use of a thermal cement, Omega OB 400.

2.4.4 Baseline Installation Procedures

In the laboratory, 16 baseline sensors (thermistors) were affixed to the pavement surface using Omega OB 400 thermal cement. Each baseline sensor was installed approximately six inches from its respective subject sensor. In the field, six baseline sensors were installed into shallow (0.25-inch deep) slots cut into the pavement. The slots were used to protect the baseline sensors from vehicle traffic. Each baseline sensor was installed within several feet of its respective subject sensors.

The first 12 to 24 inches of the test leads for baseline pavement-mounted sensors were mounted in contact with the slab and insulated from the air with ½" wide duct tape. The thermistor end of the baseline sensors was affixed to the pavement with thermal epoxy.

To provide ambient air temperature data, two baseline sensors were suspended from wood frames approximately three feet above the test sections.

The baseline sensors mounted to the test sections remained in place for all tests in the environmental chamber. Following the controlled laboratory testing, the baseline sensors were carefully removed and reused for the field evaluation portion of the project.

2.5 Statistical Methods

This section presents the statistical analysis techniques that were used to quantify the differences between sensor readings and baseline data sources. Several different statistical test analyses were conducted.

2.5.1 Accuracy

Accuracy is defined as the difference between the sensor reading and baseline data. Accuracy was quantified with the following statistical methods.

- *Mean Difference* is the average difference of all sensor readings. This value is useful in identifying the general trend or bias in sensor performance. However, it can hide sensor errors because high and low readings are averaged, which may result in a little net error overall. The mean values are presented in Appendix E, Detailed Test Results.

- *Mean Absolute Difference* is the average of the absolute values of the differences between the sensor and baseline readings. This value does not allow high and low values to cancel each other because the absolute value of each difference is measured. The mean absolute difference was selected as the primary performance measure for summarizing the test results because the values are readily understood by a diverse audience.

- *Root Mean Square Difference* also does not allow high and low values to cancel each other out. Additionally, it is more sensitive to data points that are further from the mean. For example, a sensor that provided five out of five readings that were 1° C different would have a lower root mean square than a sensor that had four accurate readings and a fifth reading that was 5° C different. Root mean square values are presented in Appendix E: Detailed Test Results.

- *Scatter Plots* were used to graphically display the raw baseline and subject sensor data. Visually comparing scatter plots can be an excellent method of detecting trends and variations between the different sensors and/or tests. Appendix E contains the scatter plots for all tests.

2.5.2 Statistical Significance

Statistical significance testing was performed to provide a tangible, objective method of determining whether or not a subject sensor's test performance differed significantly from its corresponding baseline sensor. The statistical significance testing was designed to be an additional tool for the reader to use in comparing subject sensor performance. This is not intended to classify sensor performance as "good" or "bad."

The statistical significance testing was performed in a spreadsheet using a two tailed, two sample Z-test. The test used the variance of each data set (baseline and subject sensor) along with a confidence factor (95%) to determine whether the mean values, for the baseline and subject sensor data, were "significantly" different. Tests that contained less than 30 data points were omitted from statistical testing. Sample sizes less than approximately 30 magnified the significance level to a point where nearly every data set was "statistically different." Caution is advised when interpreting the significance data.

The results of the statistical significance testing are presented in Appendix D. Overall, the statistical significance difference results reinforced the trends shown by the mean absolute error values. Typically, sensors with smaller error values (often less than 1.0° C) were determined not to be statistically different than their corresponding baseline sensor. Conversely, subject sensors with larger error values (often greater than 1.0° C) were typically determined to be statistically different than the baseline sensor.

It should be noted that the statistical significance can be affected by the variance of the test data. For example, if the variance of the baseline and subject sensor is relatively small, the statistical significance threshold will be smaller for that data; small errors will be deemed statistically significant. The reverse is also true. Relatively large variances will result in higher statistical significance thresholds.

The main application of the statistical significance tests, as presented in this project, is to aid in performance differentiation between several sensors (on a given test) with similar mean absolute error values. However, this analysis will be left up to the reader. The purpose of this report was to present the facts and summarize the general results of the tests, not to provide individual recommendations.

3 Test Plans

The goal of this study was to measure and compare the pavement surface temperature reporting performance of various models of pavement temperature sensors in various environmental conditions. This goal was divided into three separate test plans: assess sensor performance in a controlled climate, with de-icing chemicals and in field tests. Each test plan consisted of a series of specific test objectives to further measure sensor accuracy under a variety of environmental conditions. Lastly, each test objective was conducted using both concrete and asphalt pavements to investigate the effects that pavement type might have on sensor performance. The test plans and objectives are listed below:

Test Plan 1: Controlled Climate Tests

Objective 1-1	Fixed Temperature
Objective 1-2	Varying Temperature
Objective 1-3	Mobile Sensor Acclimation Time
Objective 1-4	Varied Mobile Sensor Height
Objective 1-5	Cold Day with and without Direct Solar Impact
Objective 1-6	Warm Pavement with Snowfall
Objective 1-7	Cold Pavement with Rainfall
Objective 1-8	Iced Pavement with Rainfall
Objective 1-9	Compacted Snow (melting)
Objective 1-10	Frost Depositing
Objective 1-11	Mobile Sensor Performance in Varying Ambient Temperature

Test Plan 2: De-icing Chemical Tests

Objective 2-1	Sodium Chloride - Cold Day with and without Direct Solar Impact
Objective 2-2	Sodium Chloride - Warm Pavement with Snowfall
Objective 2-3	Sodium Chloride - Cold Pavement with Rainfall
Objective 2-4	Sodium Chloride - Iced Pavement with Rainfall

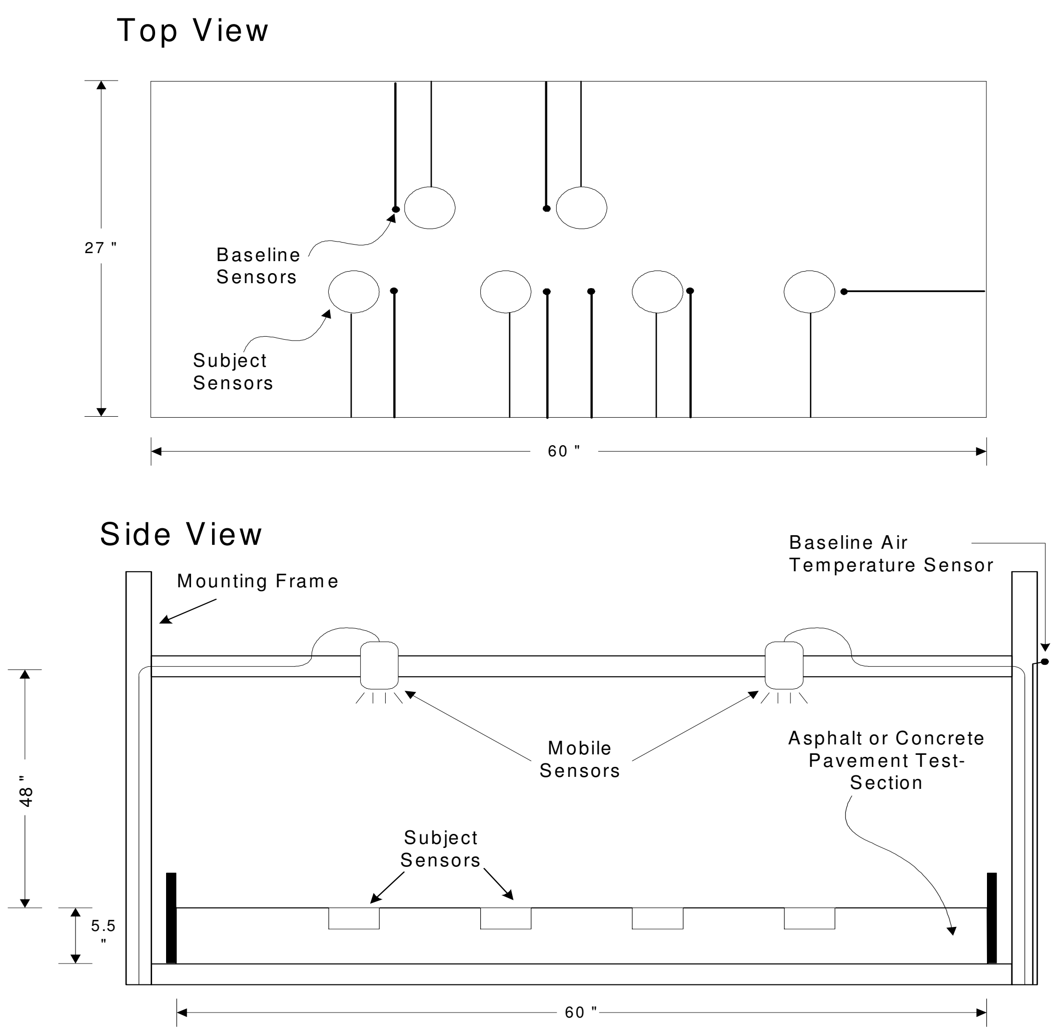
Test Plan 3: Field Tests

Objective 3-1	Field - Cold Day with and without Direct Solar Impact
Objective 3-2	Field - Cold Night with and without Strong Radiational Cooling
Objective 3-3	Field - Warm Pavement with Snowfall
Objective 3-4	Field - Cold Pavement with Rainfall
Objective 3-5	Field - Iced Pavement with Rainfall
Objective 3-6	Field - Mobile Sensor Field Evaluation

3.1 Test Plan 1: Controlled Climate Tests

This section presents the approach used to evaluate pavement temperature sensors in a controlled climate. The controlled climate tests were designed to provide accurate, repeatable and reproducible results. Two pavement test-sections (one asphalt and one concrete) served as test platforms for evaluating the subject sensors in the laboratory. One subject sensor of each type was installed in each of these test sections. The test sections measured approximately 27-inches wide by 60-inches long by 5.5-inches deep and weighed approximately 500 lbs. Test section size was selected to accommodate up to nine different fixed subject sensors while still being small enough to be maneuverable. A schematic diagram is shown in Figure 4.

Figure 4
Schematic of the Pavement Test Section and Mobile Sensor Installation



The concrete test section was made according to Mn/DOT Standard Construction Specification Number 2301 [2] and used a type of concrete that is typical for highway construction. The concrete was poured into a wood frame measuring approximately 27-inches wide by 60-inches long by 5.5-inches deep. The concrete was vibrated to remove air voids. After the concrete had hardened, the wood frame was removed. Figures 5, 6, 7 and 8 are pictures of the concrete test section.

The asphalt test section was obtained by excavating a section of in-place asphalt located at Mn/DOT's Mn/ROAD research facility. The test section had the same dimensions as the concrete test section. After excavation the asphalt section was mounted onto a metal base-plate to provide structural strength for the asphalt during transport and sensor installation. A one-inch layer of concrete was placed between the asphalt and steel plate in order to support the low and high points of the underside of the asphalt. Forklifts were used to move the sections. Refer to Figures 9 through 13 for pictures of the asphalt excavation and sensor installation. Notice that the crack visible between the different layers of asphalt in Figure 9 was caused by the stress of moving the slab. The crack closed when the sample was placed on the metal base-plate.

The six chosen models of fixed sensors were installed in both the concrete and asphalt test sections according to vendor specifications and the procedures recommended in SHRP report number H-351 (RWIS, Volume II Implementation Guide) [3]. The core drilling and saw cutting were carefully performed to minimize cracking and breakage of the test sections. All cutting and drilling was performed prior to sensor installation. Vendors were offered the opportunity to participate on-site in the installation of their sensors.

Figure 5
Saw Cutting and Drilling of Laboratory Concrete Test Section

Figure 6
Concrete Core Drilling in Preparation for Sensor Installation

Figure 7
Concrete Sensor Installation

Figure 8
Laboratory Sensor Locations (Concrete)

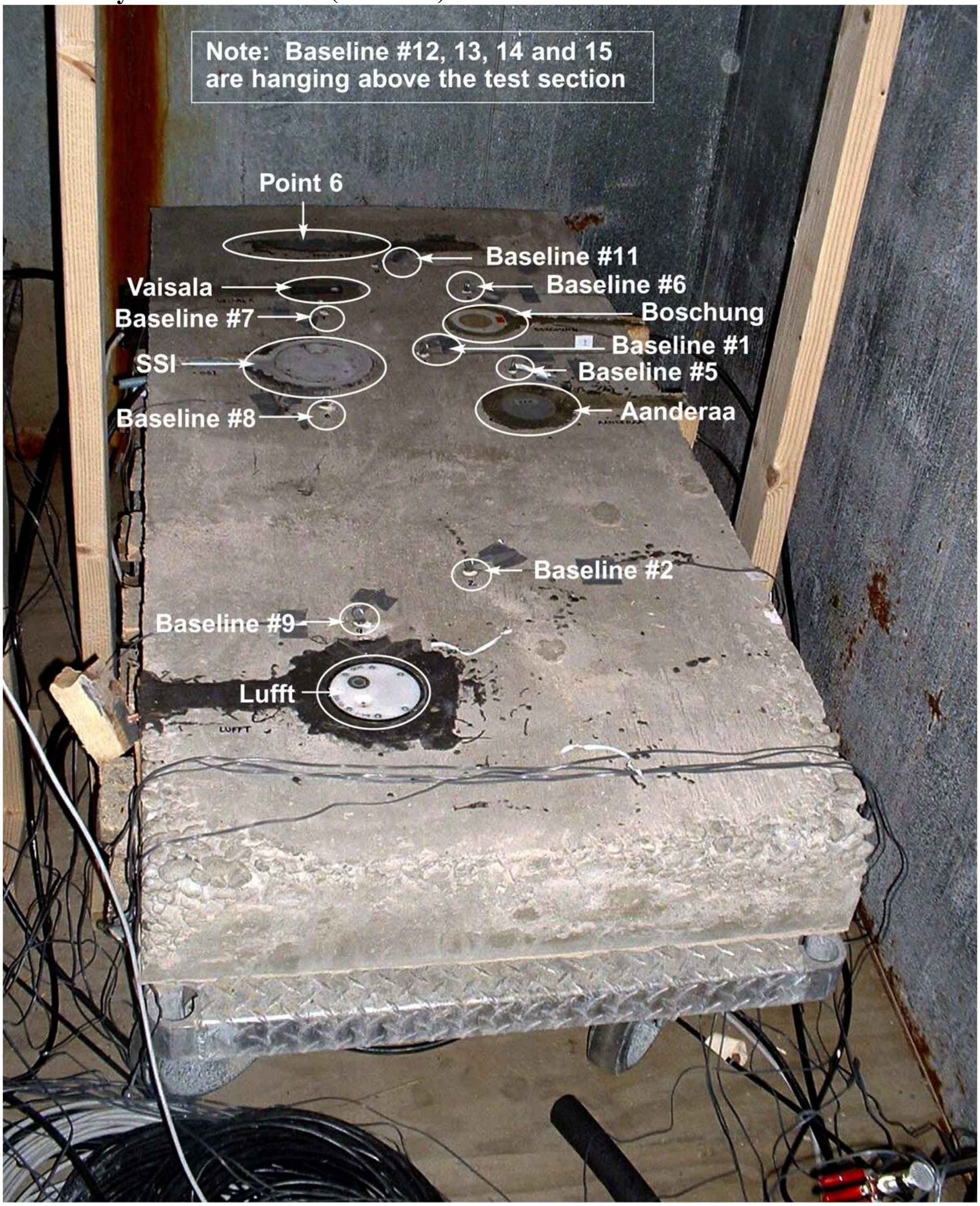


Figure 9
Removal of Asphalt Test Section at Mn/ROAD Facility

Figure 10
Placement of Asphalt Test Section on Concrete and Steel Plate

Figure 11
Asphalt Core Drilling in Preparation for Sensor Installation

Figure 12
Asphalt Sensor Installation

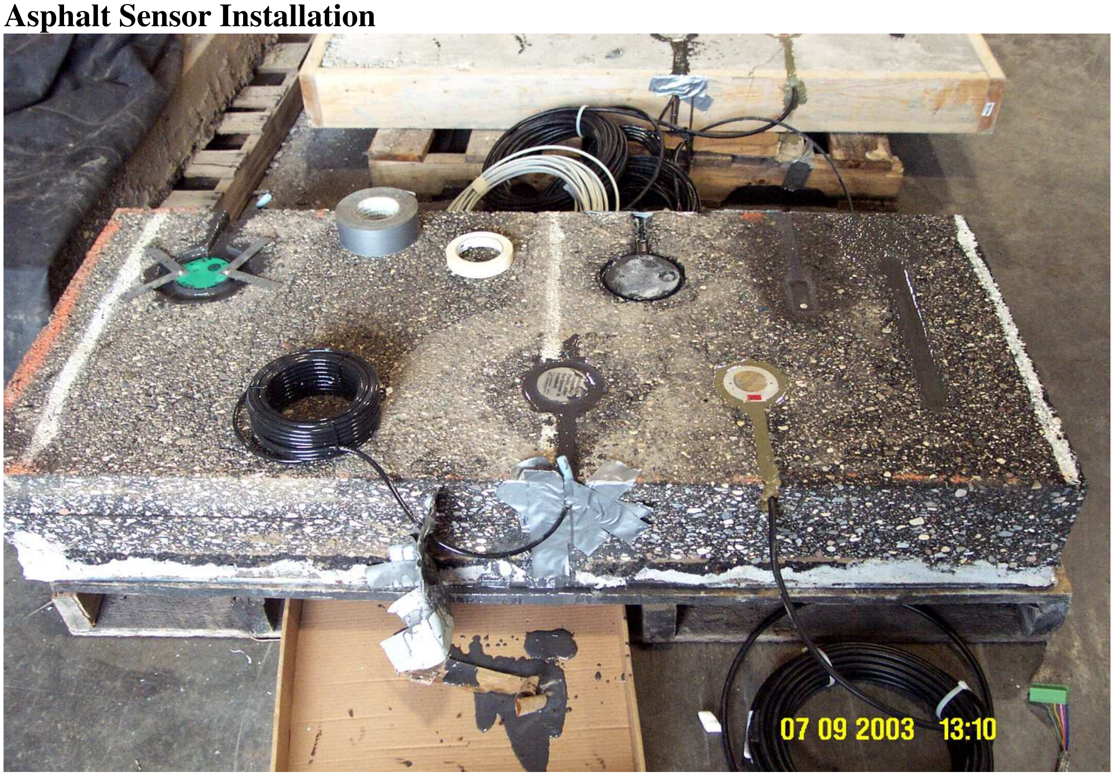
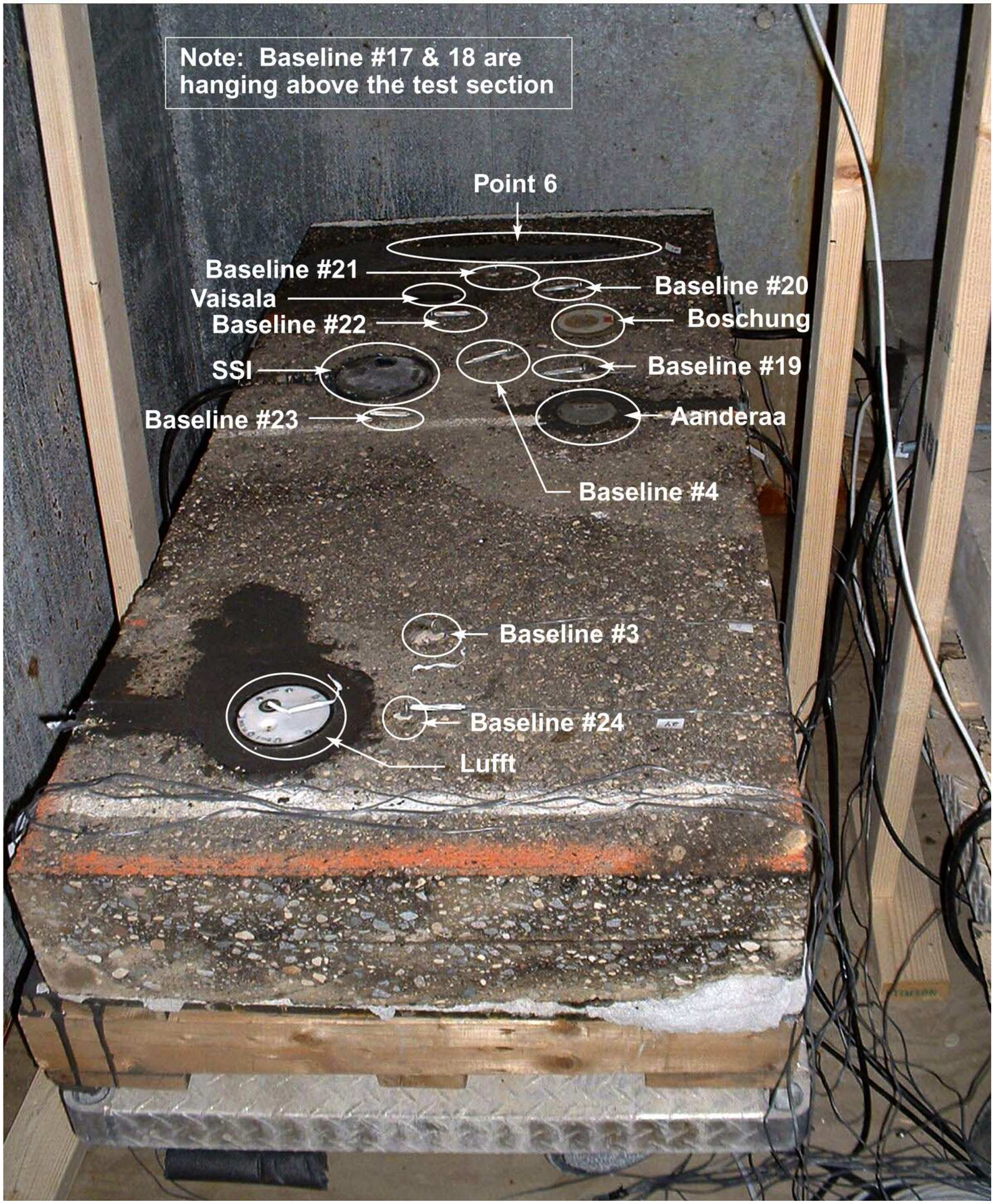


Figure 13
Laboratory Sensor Locations (Asphalt)



The test sections were then carefully transported to the Braun test facility. The test sections were placed on wood pallets and then placed on metal dollies to facilitate movement in and out of the environmental test chamber. The tests were conducted with the test sections resting on the wood pallets and dollies. A two-inch aluminum barrier was constructed around the exterior edge of each test section to hold snow/ice in place during testing. The barrier was installed such that it did not retain water.

It is important to note that evaluation of the pavement test sections on pallets and dollies differs from a real world pavement because the undersides of the sections are exposed to the air. In the real world, the pavement is in contact with the ground, a significant heat source and heat sink. Also, the sections were exposed to the air, not surrounded by pavement or other material. These factors cause the thermal properties of the pavement to differ from a real world environment by an unknown amount. Due to space considerations, these differences are inherent limitations of the tests.

Mobile sensors were installed on a framework centered above the test sections at a height of four feet in all cases except the varied height tests described in Objective 1-4. This height was chosen because it represented a typical installation height on a deployed vehicle. This height also conformed to each manufacturers' recommended installation height; Sprague required the sensor to be mounted a minimum of 20 inches above the pavement surface. Control Products stated that the sensor could be installed at any height. See Figure 4 for a schematic diagram and Figure 14 for placement in the test chamber.

The Braun environmental chamber was used to conduct the laboratory portion of the test. This chamber is a walk-in seven feet wide by eight feet high by nine feet deep chamber with temperature range from -23º C to +38º C (-10º F to 100º F). The door opening is 35 3/4" wide. The chamber is capable of maintaining a stable temperature that varies by approximately 0.5º C (1.0º F). The chamber temperature variation is created as the cooling unit cycles on and off in response to the thermostat. Both fixed and mobile sensors were evaluated using the environmental chamber. Figure 14 is a picture of the inside of the test chamber.

Sensor data output from the subject sensors and baseline sensors were collected according to the following criteria, unless otherwise noted:

- Baseline temperature data was collected at least to the nearest 0.01° C.
- Subject temperature data was collected at least to the nearest 0.1° C (except for Sprague sensor data resolution was to only the nearest 0.55° C).
- Data was automatically collected once every two minutes or less.
- Vaisala sensor data was collected every 10 minutes due to the sensor's RPU data storage limitations.
- All incoming data included a time stamp.

Figure 14
Laboratory Test Chamber

***Note the mobile sensor installation above the test sections**

Each specific test objective is described as follows:

3.1.1 Objective 1-1: Fixed Temperature

The objective of this test was to evaluate subject sensor performance at different constant temperatures. Subject sensors were evaluated against baseline readings at each given temperature. For each test, the temperatures of the pavement test sections were stabilized in the environmental chamber. Once stabilized, baseline and subject sensor data was collected for approximately 30 minutes. The subject sensors were evaluated at the following four different temperatures:

Objective 1-1a: Warm (5° C (41° F)) – Above this point, application of de-icing and anti-icing chemical is typically not required.

Objective 1-1b: Freezing point (0 ° C, 32° F) – The critical temperature range where ice begins to form and frost may form.

Objective 1-1c: Cold (-6° C, 21° F) –Near the lower end of the temperature range where NaCl application typically works well.

Objective 1-1d: Very Cold (-17° C, 1° F) – Temperature below which NaCl is not typically applied.

3.1.2 Objective 1-2: Varying Temperature

Objective 1-2a: This test captured the temperature outputs of the subject sensors and baseline sensors in a *declining* temperature environment. The purpose of these varying temperature tests was to simulate real-world conditions where temperatures can quickly rise and fall. To conduct this test, the pavement test section was brought to a stable temperature of approximately 16° C (60° F) in the test chamber. Next, the test chamber was programmed to gradually lower the temperature of the air in the chamber until it reached -17° C (1° F). The chamber's cooling rate was approximately 5.6° C (10° F) per hour. The test was concluded when the test section temperatures have stabilized. The subject sensors were evaluated against baseline readings during the pavement cool-down.

Objective 1-2b: A second test was run to capture the temperature outputs of the subject and baseline sensors in an *increasing* temperature environment. In this test, the pavement test sections were stabilized at -17° C (1° F) in the environmental chamber and then warmed to 16° C (60° F). Similar to cooling, the rate of heating was approximately 5.6° C (10° F) per hour. The subject sensors were evaluated against baseline readings during the pavement warm-up.

3.1.3 Objective 1-3: Mobile Sensor Acclimation Time

This test measured the time required for the *mobile* sensors to stabilize at a reading when moved from a warm environment to a cold environment. Acclimation time tests were conducted at four different temperatures. The goal of these tests was to simulate a typical operation in which a truck with a mobile sensor is parked inside a heated garage and then driven out into a cold environment.

In each case, the mobile sensors were first brought to a stable temperature outside of the environmental test chamber. Room temperature was approximately 16° C (60° F)). A minimum of two hours was allotted for the mobile sensors to stabilize at room temperature. Next, the mobile sensors were brought into the environmental chamber to measure stabilized pavement temperatures of -17° , -7° , 0° , and 6° C (1, 19, 32, and 43° F).

The test data was analyzed to quantify how long it took the sensors to report a stabilized reading of the pavement's temperature. The times required to reach three specific temperature thresholds were obtained. First, the time for the mobile sensors to report the pavement temperature to within 10.0° C (18° F) was recorded. As the test continued, the mobile sensors acclimated and the readings became more accurate. Next, the time to report the pavement temperature to within 5.0° C (9° F) was recorded. This continued until each mobile sensor provided a reading that was within 1.0° C (1.8° F) of the baseline sensors. The test was given a time limit of 5 hours.

Objective 1-3a: Time to acclimate with pavement at 6° C (43° F).

***Objective 1-3b**:* Time to acclimate with pavement at 0° C (32° F).

Objective 1-3c: Time to acclimate with pavement at -7° C (19° F).

***Objective 1-3d**:* Time to acclimate with pavement at -17° C (1° F).

3.1.4 Objective 1-4: Varied Mobile Sensor Height

The purpose of this test was to determine the effects of mounting height on sensor accuracy (mobile sensors only). The relevance of this test is that in practice, mobile sensors are mounted on variety of vehicles and in varying positions that affects sensor mounting height. However, there is little documentation regarding the relation between sensor height and accuracy.

The Sprague sensor's recommended mounting height was at least 20 inches above the pavement surface. The Control Products installation manual stated that their sensor could be installed at any height.

For this test, each mobile sensor was installed on a variable height structure and aimed directly down at the center of the concrete and asphalt test sections. The mobile sensors were carefully aimed to ensure that only the asphalt/concrete portions of the test sections are in sensor's field of view, not other in-pavement sensors or the chamber floor. This was important because the emissivity value of the in-pavement sensor surfaces is different than the nearby pavement.

Before the test, the mobile sensors and test sections were allowed to stabilize at one of four temperatures, -17° , -5° , 0° and 6° C (1, 23, 32 and 43° F). For each temperature setting, the mobile sensors were tested at four different mounting heights, resulting in a total of 16 different tests. After adjusting the sensor to each mounting height, the sensor was allowed to stabilize for a minimum of five minutes. After stabilization, data was collected for approximately 30 minutes. Tests were conducted at the following heights above the pavement: 1-foot, 2 feet, 3 feet and 4 feet. Higher mounting locations were not possible because of test chamber height limitations.

However, this test does not account for conditions that would be encountered in an actual deployment. These other environmental factors include roadway sand/salt/water spray, vibrations, pavement variations or the thermal effects of nearby objects including vehicle engines or exhaust systems.

***Objective 1-4a**:* Varied Mobile Sensor Height at temperature of 6° C (43° F).

***Objective 1-4b**:* Varied Mobile Sensor Height at temperature of 0° C (32° F).

***Objective 1-4c**:* Varied Mobile Sensor Height at temperature of -5° C (23° F).

***Objective 1-4d**:* Varied Mobile Sensor Height at temperature of -17° C (1° F).

3.1.5 Objective 1-5: Cold Day With and Without Direct Solar Impact

Objective 1-5a: To simulate a cold day *without* direct solar impact, the pavement test-sections were placed in the environmental chamber and allowed to stabilize at a temperature of -7° C (19° F). Data from the subject and baseline sensors were then collected for approximately 25 minutes.

Objective 1-5b: To simulate a cold day *with* direct solar impact, a sunlight-simulator (two 500-watt halogen lights) was placed above each pavement test-section and illuminated to simulate solar radiation. See Figure 15 for a picture taken during the solar impact test. The intent was to find a low-cost sunlight simulator that had energy output characteristics similar to sunlight (i.e., similar energy output in infrared, visible and ultraviolet wavelengths). The lighting was turned on and the baseline and subject sensor values were then recorded for approximately four hours.

Figure 15
Laboratory Solar Impact Test

3.1.6 Objective 1-6: Warm Pavement With Snowfall

Since snowfall is a difficult phenomenon to artificially replicate, this test condition was performed by distributing finely shaved ice across the pavement test surface.

First, ice shaved by a Zamboni® was collected from a local ice skating arena and then allowed to reach a stable temperature of -6° C (21° F) in a separate environmental chamber. The primary chamber containing the pavement section was set to 5° C (41° F) and allowed to stabilize. Sensor values were recorded at this stable condition. Next, the shaved ice was placed on the test section and evenly distributed in small increments using a broom. The shaved ice was distributed such that two inches had accumulated after 15 minutes. The 2-inch barrier around the exterior of the test sections kept the crushed ice in place, but allowed melt water to drain from the pavement surface. Sensor readings were recorded throughout the application process and during the four hours that followed.

3.1.7 Objective 1-7: Cold Pavement With Rainfall

For this test the environmental chamber was stabilized at a temperature of -7° C (19° F). A spray tank filled with distilled water was cooled to a stable temperature of 2° C (35° F) in a separate environmental chamber. A mist was then sprayed over the pavement test-section to simulate a light rain. The mist was applied incrementally to avoid pooling and run-off. Water was applied such that 0.2-inches of ice had accumulated in 30 to 60 minutes. Sensor values were automatically recorded throughout this test and during the following four hours.

3.1.8 Objective 1-8: Iced Pavement With Rainfall

At the conclusion of the above test, the iced-over -7° C (19° F) pavement test-sections were again sprayed with a 2° C (35° F) mist of distilled water to simulate rain. The mist was applied incrementally to avoid pooling and runoff. The water was applied such that 0.2-inches of ice accumulated in 30 to 60 minutes. The goal of this test was to simulate iced pavement with rainfall. Sensor values were automatically recorded throughout this test and for the following four hours. The asphalt test section following the rainfall test is shown in Figure 16; note the layer of ice across the pavement.

Figure 16
Cold Pavement After Simulated Rainfall Test (Asphalt)

3.1.9 Objective 1-9: Compacted Snow (Melting)

For this test, the pavement sections were cleared of all moisture and cooled to a stable temperature of 0° C (32° F). Shaved ice was then collected and allowed to reach a stable temperature of -6° C (21° F) in a separate environmental chamber. Next, the shaved ice was distributed across the pavement to a uniform depth. Then the shaved ice was evenly compacted to simulate compacted snow. The temperature of the pavement section was allowed to stabilize at 0° C (32° F).

Once the pavement section temperatures had stabilized at 0° C (32° F), the chamber temperature was gradually increased at a rate of approximately 5.6° C (10° F) per hour until all the snow had melted, and the test was complete.

The test sections were equipped with a two-inch high barrier around the perimeter to contain the snow. The barrier was designed to allow water from the melting snow to drain off the pavement surface.

3.1.10 Objective 1-10: Frost Depositing

The objective of this test was to create and document the formation of frost on the test sections of the pavement. First, the environmental test chamber and test sections were allowed to stabilize at a temperature of -6° C (21° F). Next, humidity in the test chamber had to be increased in order to facilitate the formation of frost.

An obstacle was encountered while trying to raise the humidity within the test chamber. The ambient moisture was condensing out of the air, onto the cooling fins inside the air conditioning unit while the -6° C (21° F) temperature was being maintained. To counteract this obstacle, a large cooler full of hot tap water was placed in the chamber and continuously stirred during the test to rapidly increase the relative humidity in the chamber. This added moisture was then deposited as frost on the test sections.

The test technician observed and recorded the point when frost formation was first visible on the pavement surfaces. Baseline and subject sensor values were automatically recorded throughout the procedure and for one hour after the formation of frost.

3.1.11 Objective 1-11: Mobile Sensor Performance in Varying Ambient Temperature

This test was used to determine the effect of ambient air temperature on sensor readings when the two mobile sensors were aimed at a target of constant temperature. To conduct this test, the mobile sensors were removed from the chamber and installed above an ice/water bath. The ambient temperature in the room of the ice bath was approximately 18° C (65° F). After the mobile sensor readings stabilized, five readings were recorded over 10 minutes. Next, the mobile sensors and ice water bath were brought into the chamber which had been cooled to a stable temperature of 0° C (32° F). Readings were recorded over the next hour.

3.2 Test Plan 2: De-icing Chemical Tests

Both anti-icing and de-icing applications are commonly used to prevent pavement surfaces from icing. Anti-icing refers to the spraying of a chemical onto pavement surfaces before the ice development or snow events. Deicing generally refers to the spreading of pre-wetted solid sodium chloride (NaCl) onto pavement surfaces after the ice or snow events. For both methods, the applied chemical lowers the freezing/melting point of water/ice, resulting in wet road surface conditions instead of icy and slippery conditions.

The general procedures and sequences for comparing the sensors under chemical test conditions were similar to the procedures outlined in Test Plan 1. All chemical tests were conducted in the environmental test chamber.

The NaCl used in this test was obtained from Mn/DOT, which was one of the Aurora agencies involved in the study. The liquid 23% by NaCl by weight mixture was applied at a rate of 25 to 40 gallons per lane mile. Application rates were obtained from Guideline 35.25 in the Wisconsin Department of Transportation (another Aurora member agency) *State Highway Maintenance Manual*. These guidelines are provided in Appendix C.

A spray tank filled with the NaCl mixture was cooled to 2° C (35° F) in order to approximate actual application temperatures. The NaCl solution was then sprayed onto the pavement test sections and housings of the mobile sensors in order to simulate an actual deployment in which sensors are subjected to salt spray. Note that the NaCl solution did not come in direct contact with the optical lenses of the mobile sensors. An actual field deployment would subject the sensors to additional roadway spray. The following objectives were tested:

3.2.1 Objective 2-1: Sodium Chloride – Cold Day With and Without Direct Solar Impact

This test followed the same procedures as Objective 1-5, except the NaCl mixture was applied prior to the start of the test. The pavement temperature for this test was -7° C (19° F) and an application of 25 gallons of liquid salt mixture per lane mile was applied. This application rate was derived from the Appendix C guidance for a predicted event of frost or black ice.

Objective 2-1a*:* To simulate a cold day *without* direct solar impact, the pavement test-sections were placed in the environmental chamber and allowed to stabilize at a temperature of -7°C (19°F). Data from the subject and baseline sensors were then collected for approximately 25 minutes.

Objective 2-1b: To simulate a cold day *with* direct solar impact, two 500-watt halogen lights were placed above each pavement test-section and illuminated to simulate solar radiation. After the lights were switched on, the baseline and subject sensor values were recorded for approximately four hours.

3.2.2 Objective 2-2: Sodium Chloride – Warm Pavement With Snowfall

This test followed the same procedures as Objective 1-6, except the NaCl mixture was applied prior to the start of the test and directly applied to the mobile sensors. The pavement temperature for this test was 4° C (39° F) and an application of 40 gallons of liquid salt mixture per lane mile was applied. This application rate was derived from the Appendix C guidance for a predicted precipitation event of moderate or heavy snow (more than ½ inch per hour).

3.2.3 Objective 2-3: Sodium Chloride – Cold Pavement With Rainfall

This test used the same procedure as Objective 1-7, except the NaCl mixture was applied prior to the start of the test. The pavement temperature for this test was -6° C (21° F) and an application of 30 gallons of liquid salt mixture per lane mile was applied. This application rate was derived from the Appendix C guidance for a predicted precipitation event of light snow (less than ½ inch per hour).

3.2.4 Objective 2-4: Sodium Chloride – Iced Pavement With Rainfall

This test used the same procedure as Objective 1-8, except the NaCl mixture was applied prior to the start of the test. The pavement temperature for this test was -6° C (21° F) and an application of 30 gallons of liquid salt mixture per lane mile was applied. Note that this test immediately followed the previous test, simulating a condition in which chemicals were applied before and after a weather event. Therefore, the application rate selected is for a *repeat application* as indicated in the guideline in Appendix C for a predicted precipitation event of light snow (less than ½ inch per hour).

3.3 Test Plan 3: Field Tests

The following field tests were conducted at the Mn/DOT's Mn/ROAD research facility near Monticello, Minnesota. New sensors were installed into the in-place pavement (concrete and asphalt) on a low volume test road. The test road had occasional passenger vehicle and semi-truck traffic driven at periodic intervals for pavement research purposes. The test road was otherwise closed to public traffic. The purposes of these tests were to analyze sensor performance under "real world" conditions and compare this data with the previous laboratory data. See Figures 17 through 21 for pictures of sensor installation and placement at the field test facility. Also note the baseline sensor installed to the right of the sensor in Figure 19.

The Point Six sensor was installed in the field, but repeated attempts to establish communication with the sensor failed. The vendor indicated they were satisfied with the results from the laboratory tests and asked to be withdrawn from the field testing.

Figure 17
Pavement Preparation for sensor Installation (Saw Cutting)

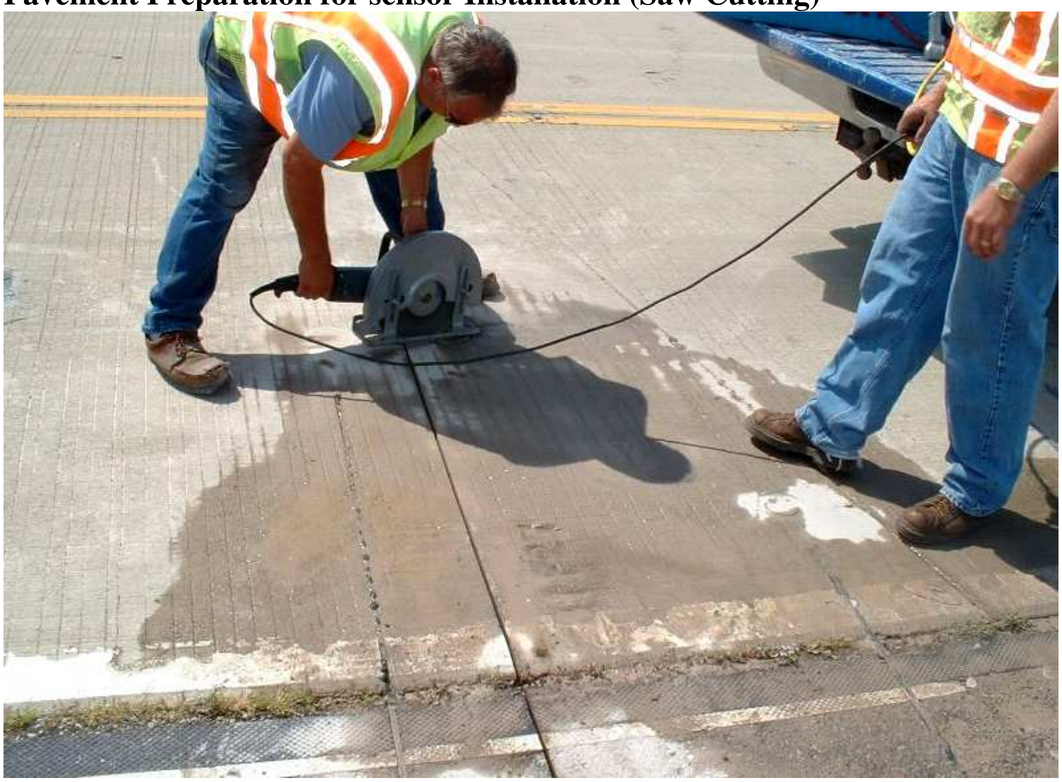


Figure 18
Field Sensor Placement

Figure 19
Final Sensor and Baseline Installation

Figure 20
Field Sensor Locations – Asphalt

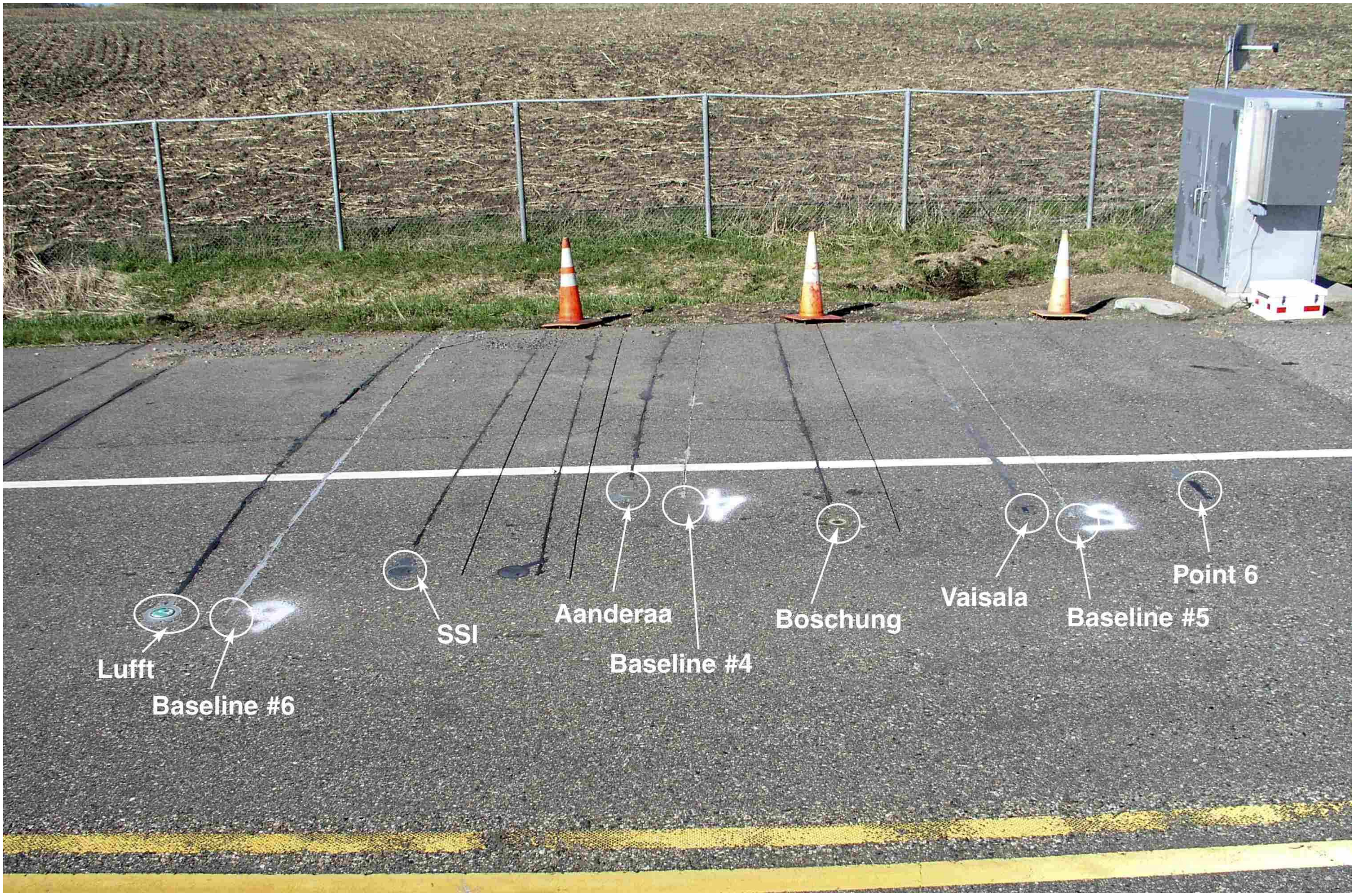
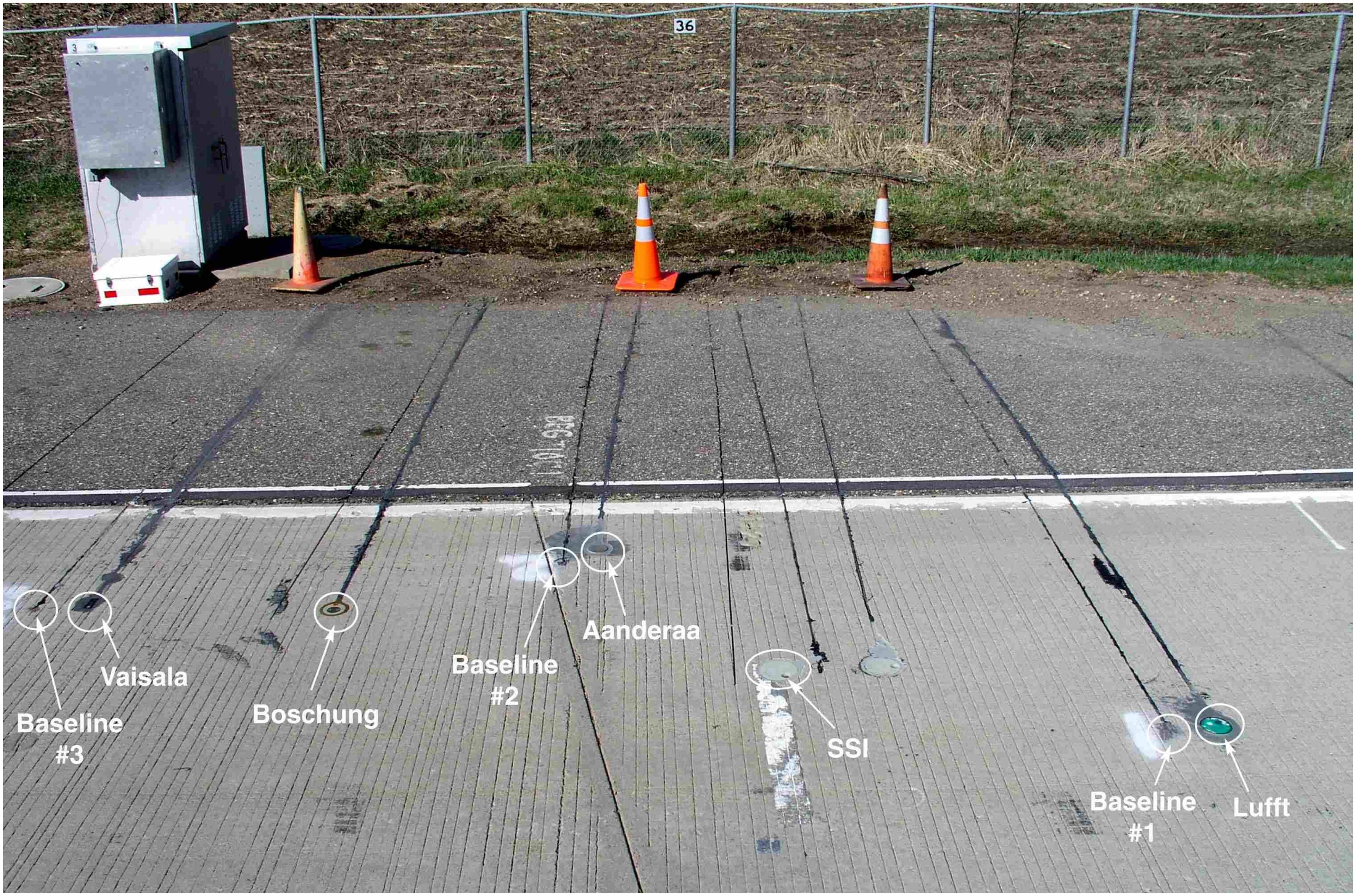


Figure 21
Field Sensor Locations – Concrete



3.3.1 Objective 3-1: Cold day With and Without Direct Solar Impact

Objective 3-1a: For cold day (temperatures less than 0° C (32° F)) *with* direct solar impact, data was collected on a day with no cloud cover.

Objective 3-1b: For cold day (temperatures less than 0° C (32° F)) *without* direct solar impact, data was collected on a day with cloud cover.

3.3.2 Objective 3-2: Cold night With and Without Strong Radiational Cooling

***Objective 3-2a*:** For the cold night *without* strong radiational cooling, data was collected on an overcast night with a low temperature of approximately 7° C (45° F).

***Objective 3-2b*:** For the cold night *with* strong radiational cooling, data was collected on a clear night with temperatures of approximately 0° C (32° F). These conditions were chosen because there was no incoming radiation from the sun or downward radiation from the clouds. The pavement radiates heat to the atmosphere, but the clouds do not radiate heat back down to the pavement. As a result, the pavement can cool to temperatures below the ambient air temperature.

3.3.3 Objective 3-3: Warm Pavement With Snowfall

This test was conducted when the pavement temperature was approximately 7° C (45° F) and the pavement was clear of snow and ice. Since natural snowfall is difficult to predict, artificial snow was manually distributed over the subject and baseline sensors. Crushed ice (ranging from dust to pea size particles) was used as the artificial snow. Sensor readings were recorded throughout the application process and for the following four hours.

3.3.4 Objective 3-4: Cold Pavement With Rainfall

This test was conducted when the ambient air temperature was approximately -12° C (9° F) and the pavement was clear of snow and ice. A spray tank was filled with distilled water and was cooled to a stable temperature of 2° C (35° F). Next, a fine mist was sprayed over the pavement test-sections to simulate a light rain. Refer to Figure 22 for a picture of the rainfall test.

3.3.5 Objective 3-5: Iced Pavement With Rainfall

At the conclusion of the previous test, the iced-over pavement was again sprayed with a fine 2° C (35° F) mist of distilled water to simulate rain. The goal of this test was to simulate iced pavement with rainfall.

3.3.6 Objective 3-6: Mobile Sensor Field Evaluation

Mobile sensor performance was evaluated in the field by mounting the sensors to a platform that was then attached to the front bumper of a passenger vehicle. See Figures 23 and 24 for pictures of the mobile sensor set-up; these pictures were taken during an ice bath test.

Figure 22
Cold Pavement With Simulated Rainfall Test

Figure 23
Mobile Ice-bath Set-up for Field Testing

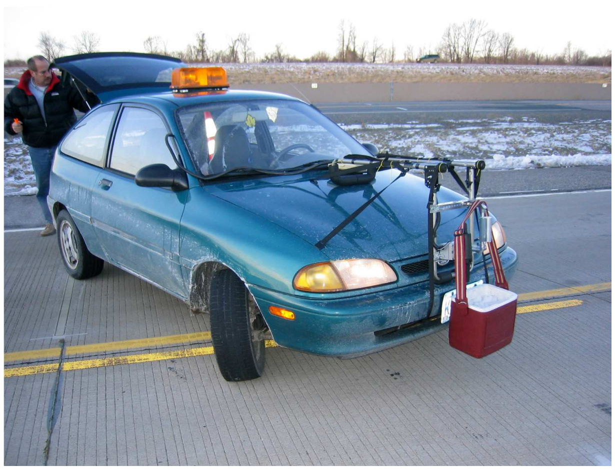


Figure 24
Mobile Ice-bath Set-up for Field Testing (Close-up)

An ice bath was used to check for proper calibration of the Control Products sensor before the start of each day of testing. The calibration check was performed once the Control Products sensor had been exposed to the ambient air temperature for at least 90 minutes. The calibration procedure provided in the owner's manual was followed. It should be noted that there was no manufacturer provision for Sprague field calibration.

The sensors were driven through the Mn/ROAD test facility in order to capture pavement temperatures. Temperature data was captured in 3-second intervals in order to provide a detailed record of pavement temperatures over time. The following specific test scenarios were conducted:

Objective 3-6a Cold Pavement With Rainfall: This test captured cold pavement (-9.0° C (-16° F)) with rainfall. The mobile data was collected by parking the test vehicle over the baseline sensors after water was applied to the test section.

Objective 3-6b Ice Bath Test: The ice bath comparison test was designed to compare the temperature readings of both mobile sensors to an ice bath while the vehicle is driven at the Mn/ROAD test facility. Additionally, the test was conducted to determine the effect of ambient air temperature on the sensors' readings. Ideally, this test would have been conducted over a long stretch of road with widely varying air temperatures, but this was not possible due to the short length of the test track.

Throughout this test, both sensors were aimed at an ice bath mounted to the front of the vehicle and positioned underneath the sensors. After a 90-minute acclimation time, a passenger vehicle, equipped with the sensors and ice bath, was driven for an hour at speeds varying between 30 and 50 miles per hour.

Objective 3-6c Emissivity Test: The emissivity test, building on work done by Ron Tabler [5], was used to determine the effect of differential emissivity on the accuracy of temperature measurements. The accuracy of mobile sensors is based on the assumption that the emissivity of concrete and asphalt are similar to ice.

The test consisted of capturing pavement temperatures with the mobile sensors before and after the pavement sections were sprayed with ice water and then comparing those readings to the baseline. The accuracy of the sensor readings from the dry and iced pavement tests was used to determine if differing emissivities had a significant effect on sensor accuracy.

4 Results

The results of the statistical analysis are presented in the appendixes. The mean absolute error was selected as the primary statistic for expressing results because it does not allow for values higher and lower than the baseline to offset each other, as would be the case with a basic mean calculation. Also, it was felt that mean absolute values are widely understood by the report's intended audience. The mean error was also incorporated for further clarification and comparison when needed. The root mean square was also calculated for each of the tests, but was not presented in the text of the report in the interest of brevity. See Appendix E for additional statistics.

The majority of the data presented in this report is unedited data captured directly from each sensor. However, there are two situations in which the raw sensor data required adjustment in order to provide an accurate picture of the sensors performance.

Control Products Mobile Sensors

The first situation involved the two Control Products mobile sensors. Upon preliminary inspection of the laboratory test results, the sensors consistently reported temperature values approximately 0.9° C higher than its baseline. Investigation suggested that the sensors may have been mis-calibrated prior to the laboratory testing. In order to test this hypothesis, the sensors were recalibrated and retested in the laboratory after the original testing was completed. It was determined that the original miscalibration occurred during an ice bath calibration procedure; the original ice bath was not mixed properly and/or was not given sufficient time for the water temperature to equilibrate.

After the Control Products sensors were carefully recalibrated, several constant and variable temperature tests were performed again in the laboratory. The average of the mean absolute errors for these tests was less than 0.1° C. Therefore, it was concluded that the Control Products sensors were miscalibrated during the initial laboratory testing.

To compensate for the miscalibration, the average of the mean absolute errors for the entire laboratory testing as calculated for the asphalt and concrete sensors. These average values, 0.84 and 1.05° C for the asphalt and concrete respectively, were assumed to be the magnitude of the initial miscalibration. These miscalibration values were then subtracted from all of the initial laboratory raw data. This modified laboratory data is presented throughout this report. It should be noted that the Control Products sensors were thoroughly re-calibrated prior to the original field testing. Additionally, analysis of the field data did not show the consistent miscalibration patterns that were present during the laboratory testing. Therefore, no adjustment was made to the field data.

Sprague Mobile Sensors

The second situation involved data captured from the Sprague sensors. Preliminary inspection of the raw data showed a significant number of erratic temperature values. Closer inspection showed that these erratic data points corresponded to the air temperature inside the laboratory test chamber. Through direct comparison of the live-sensor and the computer-recorded data, it was determined that the computer used to record the raw data was erratically capturing air temperature data points and reporting them as pavement data points. Therefore, the raw data was manually filtered to remove the obvious erratic air temperature values. This filtered data is presented throughout this report.

4.1 Summary of Results

This section of the report presents summarized findings from each of the tests. It also contains some interpretation to further explain why certain sensors may have responded to the given condition. Sections 4.2, 4.3 and 4.4 present more detailed results for each of the tests.

The test results are presented in the same order as the test plans.

– NOTE –

To minimize the amount of text in the graphs, sensors are often labeled with letters. The following list shows which sensor corresponds with each letter:

- Sensor A: Aanderaa 3565 Road Condition Sensor
- Sensor B: Boschung BOSO Passive
- Sensor C: Lufft FASS Black Ice Detector IRS-21
- Sensor D: Point Six Wireless Point Probe
- Sensor E: SSI FP-2000
- Sensor F: Vaisala DRS 511
- Sensor G: Sprague RoadWatch
- Sensor H: Control Products 999J

4.1.1 Controlled Climate and Chemical Test Summary

This section presents results and explains issues encountered in the laboratory. Because the environment could be carefully controlled, it was easier to note the differences between the sensors. This part of the testing isolated issues that affect the accuracy of the sensor compared to the baseline.

Throughout the laboratory testing, the average mean error was 0.7° C for the in-pavement sensors and 0.8° C for the mobile sensors.

The results of Test 1-5b and Test 2-1b, direct solar impact in the test laboratory, were highly varied. The variation that the baseline sensors provided when compared to one another was of particular note. Both baseline and subject sensor data varied within each pavement section. The field version of this test, Test 3-1a, reported significantly more stable and consistent temperatures. This would suggest that the laboratory procedure for simulating solar radiation was ineffective and that extreme caution should be used when analyzing sensor performance during the artificial solar testing.

Table 3: Laboratory Results Summary

Test Description:	Fixed Temperature 5º C		Fixed Temperature 0º C		Fixed Temperature -6º C		Fixed Temperature -17º C		Declining Temperature		Increasing Temperature	
TEST NO.	1-1a		1-1b		1-1c		1-1d		1-2a		1-2b	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.16	0.24	0.03	0.12	1.06	1.23	0.11	0.06	1.74	4.75	1.52	2.91
BOSCHUNG	1.82	0.19	0.20	0.16	0.22	0.19	0.06	0.06	1.22	0.26	1.10	0.36
LUFFT	0.21	0.08	0.11	0.03	0.10	0.05	0.53	0.40	0.36	0.42	0.55	0.35
POINT 6	1.60	0.89	0.38	0.74	0.20	0.07	0.23	0.27	0.54	0.29	1.43	1.17
SSI	0.45	0.49	0.40	0.30	0.73	0.58	0.74	0.60	1.23	0.97	0.14	0.15
VAISALA	0.13	0.12	0.08	0.11	0.07	0.12	0.08	0.05	0.13	0.19	1.16	0.14
SPRAGUE	0.78	0.52	1.13	0.36	1.53	0.46	1.56	0.33	N/A	0.98	N/A	0.68
CONTROL PRODUCTS	0.20	0.20	0.08	0.10	0.55	0.30	1.20	0.31	N/A	0.75	N/A	0.70

Test Description:	Cold Pavement w/o Solar Impact		Cold Pavement w/ Solar Impact		Warm Pavement w/ Snowfall		Cold Pavement w/ Rainfall		Iced Pavement w/ Rainfall		Compacted Snow (melting)	
TEST NO.	1-5a		1-5b		1-6		1-7		1-8		1-9	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.31	0.31	3.35	3.17	1.34	1.05	0.85	0.62	0.43	0.58	1.20	0.56
BOSCHUNG	0.17	0.16	0.97	0.55	0.85	0.32	0.65	0.63	0.44	0.34	0.88	0.56
LUFFT	0.16	0.06	0.23	0.16	0.46	0.15	0.90	0.92	0.31	0.30	0.55	0.60
POINT 6	0.28	0.19	0.68	1.47	0.76	0.67	1.27	0.74	0.97	0.77	0.61	1.12
SSI	0.50	0.54	2.10	1.52	0.55	0.47	1.42	1.17	0.67	1.09	0.39	0.76
VAISALA	0.07	0.08	3.35	1.23	0.79	0.76	1.17	0.75	0.89	0.62	N/A	N/A
SPRAGUE	1.13	0.47	1.15	N/A	1.01	0.37	1.96	N/A	1.98	0.83	1.39	0.63
CONTROL PRODUCTS	0.10	0.15	2.80	0.63	0.56	0.71	0.95	0.49	0.67	0.42	1.76	0.87

Test Description:	Frost Depositing		NaCl: Cold w/o Solar Impact		NaCl: Cold w/ Solar Impact		NaCl: Warm w/ Snow		NaCl: Cold w/ Rainfall		NaCl: Iced Pavement w/ Rainfall	
TEST NO.	1-10		2-1a		2-1b		2-2		2-3		2-4	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.66	0.62	0.09	0.05	2.14	1.68	1.58	1.06	0.50	0.51	0.67	0.52
BOSCHUNG	0.52	0.22	0.22	0.18	0.51	0.46	0.28	0.63	0.37	0.26	0.45	0.26
LUFFT	0.37	0.24	0.10	0.10	0.31	0.37	1.10	0.28	0.60	0.59	N/A	N/A
POINT 6	1.27	N/A	0.18	0.14	1.76	1.17	0.72	0.57	1.08	0.56	1.34	0.74
SSI	0.38	0.32	0.62	0.43	2.62	1.44	0.44	0.51	0.68	0.77	1.10	0.97
VAISALA	0.20	0.14	N/A	N/A	2.15	1.16	0.71	0.60	0.34	0.48	0.38	0.54
SPRAGUE	1.21	N/A	0.82	N/A	0.71	N/A	0.94	N/A	1.27	N/A	2.02	N/A
CONTROL PRODUCTS	0.80	0.51	0.30	0.16	2.61	0.20	0.93	1.06	0.54	0.39	0.39	0.38

1. Values in table are Mean Absolute Differences between sensor and baseline temperature in Degrees Celsius.
2. N/A represents test data not available. See test result section for more detailed explanation.

Summary of In-Pavement Sensor Laboratory

In varying environmental testing, such as varying air temperature or adding rain and snow, some in-pavement sensors performed better than others, but most reported errors less than 1.5° C. In fact, 90 percent of the test results reported temperature errors less than 1.4° C, and the average absolute error was 0.7° C.

Many of the errors associated with the varying environmental conditions were caused by the pavement sensors reporting temperature variations at a different rate than the baseline sensors. Some pavement sensors provided more stable readings, but registered the temperature change after a delay between five to 15 minutes for precipitation events and between 15 to 50 minutes for changes in the ambient air temperature. For example, an occasional trend was that the Aanderaa and Point Six sensors took approximately 20 minutes longer than the other sensors (30 minutes instead of 10 minutes) to fully respond to the abrupt temperature decreases associated with snowfall events. This response time may be due to the location of the temperature sensing element within these sensors. For example, if the element is two inches below the pavement surface, a temperature change would not be registered until the temperature change was transmitted to the temperature sensing element. However, the thermistor baselines were mounted at the surface of the pavement and were quickly influenced by temperature changes.

Sensors that are buried below the pavement surface have some desirable qualities, such as more consistent temperature reporting when subjected to short-term influences. Because their temperature sensing elements are not at the surface, these sensors do not show rapid fluctuations when precipitation occurs. It would often be more important to know that there is a long-term dangerous condition developing than a short-term temperature change at the surface of the pavement.

In addition, the Vaisala sensor was configured to report data in 10- or 30-minute intervals while the other sensors reported data in two-minute intervals. The larger Vaisala intervals were due to the software limitations of the Vaisala-supplied RPU that only allowed for 144 data "events" to be stored. The time interval was lengthened in order to capture data over the duration of the test. It did not appear that less frequent data collection significantly affected the end result of the data analysis.

Summary of Mobile Sensor Laboratory Tests

Overall, the mobile sensors reported similar levels of performance and accuracy as the in-pavement sensors. Throughout the mobile sensor testing, reported temperature errors ranged between 0.1 and 2.0° C. Additionally, 90 percent of the test results reported temperature errors less than 1.6° C.

Tests of mobile sensors installed at different heights revealed that mounting height does not affect mobile sensor performance.

It is important to note that the mobile sensors use remote sensing technology and are not in direct contact with the pavement. Because of this indirect temperature sensing, the mobile sensors are often not able to determine the pavement temperature when the roadway surface is covered by ice and/or snow. However, throughout this study, the mobile sensors were generally able to provide accurate data, even when the pavement was covered with thin layers of ice or snow.

The Sprague mobile sensor regularly had the highest temperature variation from its baseline, often reporting a 1.0 or 1.5° C spread of temperatures on individual tests. A partial explanation for the variation is that the Sprague sensor had the lowest temperature resolution of the sensors tested, reporting temperatures to only the nearest 0.55° C.

The Sprague sensor also required an approximate 30-minute acclimation period when transferred between significantly different ambient air temperatures; for example, when transported from a warm garage to the cold outdoors. Readings taken during this acclimation period were inaccurate by up to 20° C.

Also, the Sprague sensor performance was impacted when the sensor was subjected to varying ambient air conditions when aimed at an ice bath during the change.

4.1.2 Field Test Summary

Overall, the field tests produced results that were similar to those of the laboratory. Table 4 provides a summary of the field test results.

Table 4: Field Test Summary

Test Description:	Cold Day w/ Solar Impact		Cold Day w/o Solar Impact		Cold Night w/o Radiation Cooling		Cold Night w/ Radiation Cooling	
TEST NO.	3-1a		3-1b		3-2a		3-2b	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.39	1.66	N/A	N/A	0.09	0.17	0.44	0.39
BOSCHUNG	0.58	2.05	0.29	0.92	0.76	0.74	0.61	1.01
LUFFT	0.23	1.85	0.10	1.07	0.63	0.87	0.91	1.37
SSI	0.58	1.31	0.50	0.68	0.30	0.74	0.08	0.46
VAISALA	1.49	2.25	0.94	1.37	0.98	0.94	1.09	1.01

Test Description:	Warm Pavement w/ Snowfall		Cold Pavement w/ Rainfall		Iced Pavement w/ Rainfall	
TEST NO.	3-3		3-4		3-5	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.65	1.27	1.53	1.70	0.56	1.44
BOSCHUNG	0.80	0.49	2.03	1.34	0.35	0.76
LUFFT	0.53	0.37	1.73	1.43	0.40	1.20
SSI	0.37	0.70	2.47	2.51	0.69	1.40
VAISALA	1.28	2.75	1.50	1.59	2.42	0.63

1. Values in table are Mean Absolute Differences between sensor and baseline temperature in Degrees Celsius
2. N/A represents test data not available. See test result section for more detailed explanation.

Summary of In-Pavement Sensor Field Tests

The results of the field testing showed that the in-pavement sensors performed slightly less accurately in a "real" field environment than in the laboratory. The average error reported by the in-pavement sensors was 1.0° C and 90 percent of the test results reported temperature errors less than 1.9° C.

One trend noticed at Mn/ROAD was that during the varying temperature tests (Tests 3-1 and 3-2) the subject sensors over-reported the temperature during day-time temperature increases and under-reported the pavement temperature during nighttime temperature decreases. These trends were not observed during the snow and rain tests. "Real-world" factors, such as solar radiation, radiational cooling, heating capacities or wind, may have affected sensor accuracy.

Limited conclusions could be drawn regarding the Vaisala sensor's accuracy or performance due to the large data reporting intervals of the Vaisala sensor.

Summary of Mobile Sensor Field Tests

The average mobile sensor error during the field testing (Test 3-6) was 1.2° C. During some portions of field testing, both mobile sensors would over- or under-report the true pavement temperature. The sensors accuracy during other portions of the field tests made miscalibration an unlikely cause. Differing emissivities of the pavement and/or ice could be the cause. However, further field testing is necessary to confirm this theory.

4.2 Detailed Controlled Climate Test Results

This section presents detailed results and in-depth commentary on the controlled climate tests performed in the laboratory. Table 5 below summarizes the results from the controlled climate laboratory testing.

4.2.1 Fixed Temperature Tests

Overall, most sensors reported temperatures within 1.0° C of their baseline sensors. The average error for the fixed temperature tests was 0.4° C; see the graph below for summarized data for this test. Sensors A through H are identified at the beginning of this chapter.

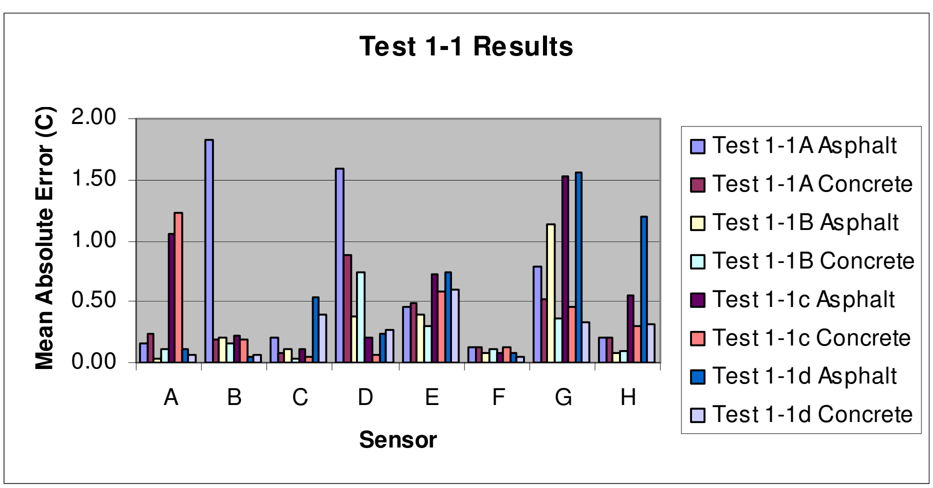


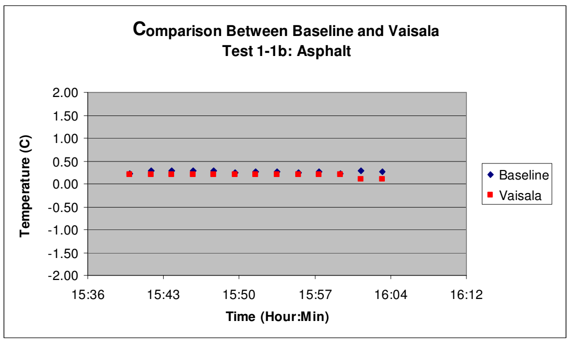
Table 5: Controlled Climate Summary

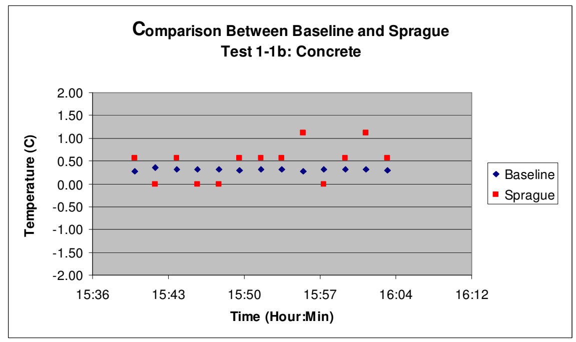
Test Description:	Fixed Temperature 5º C		Fixed Temperature 0º C		Fixed Temperature -6º C		Fixed Temperature -17º C		Declining Temperature		Increasing Temperature	
TEST NO.	**1-1a**		**1-1b**		**1-1c**		**1-1d**		**1-2a**		**1-2b**	
	Asphalt	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**
AANDERAA	0.16	0.24	0.03	0.12	1.06	1.23	0.11	0.06	1.74	4.75	1.52	2.91
BOSCHUNG	1.82	0.19	0.20	0.16	0.22	0.19	0.06	0.06	1.22	0.26	1.10	0.36
LUFFT	0.21	0.08	0.11	0.03	0.10	0.05	0.53	0.40	0.36	0.42	0.55	0.35
POINT 6	1.60	0.89	0.38	0.74	0.20	0.07	0.23	0.27	0.54	0.29	1.43	1.17
SSI	0.45	0.49	0.40	0.30	0.73	0.58	0.74	0.60	1.23	0.97	0.14	0.15
VAISALA	0.13	0.12	0.08	0.11	0.07	0.12	0.08	0.05	0.13	0.19	1.16	0.14
SPRAGUE	0.78	0.52	1.13	0.36	1.53	0.46	1.56	0.33	N/A	0.98	N/A	0.68
CONTROL PRODUCTS	0.20	0.20	0.08	0.10	0.55	0.30	1.20	0.31	N/A	0.75	N/A	0.70

Test Description:	Cold Pavement w/o Solar Impact		Cold Pavement w/ Solar Impact		Warm Pavement w/ Snowfall		Cold Pavement w/ Rainfall		Iced Pavement w/ Rainfall		Compacted Snow (melting)		Frost Depositing	
TEST NO.	**1-5a**		**1-5b**		**1-6**		**1-7**		**1-8**		**1-9**		**1-10**	
	Asphalt	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**
AANDERAA	0.31	0.31	3.35	3.17	1.34	1.05	0.85	0.62	0.43	0.58	1.20	0.56	0.66	0.62
BOSCHUNG	0.17	0.16	0.97	0.55	0.85	0.32	0.65	0.63	0.44	0.34	0.88	0.56	0.52	0.22
LUFFT	0.16	0.06	0.23	0.16	0.46	0.15	0.90	0.92	0.31	0.30	0.55	0.60	0.37	0.24
POINT 6	0.28	0.19	0.68	1.47	0.76	0.67	1.27	0.74	0.97	0.77	0.61	1.12	1.27	N/A
SSI	0.50	0.54	2.10	1.52	0.55	0.47	1.42	1.17	0.67	1.09	0.39	0.76	0.38	0.32
VAISALA	0.07	0.08	3.35	1.23	0.79	0.76	1.17	0.75	0.89	0.62	N/A	N/A	0.20	0.14
SPRAGUE	1.13	0.47	1.15	N/A	1.01	0.37	1.96	N/A	1.98	0.83	1.39	0.63	1.21	N/A
CONTROL PRODUCTS	0.10	0.15	2.80	0.63	0.56	0.71	0.95	0.49	0.67	0.42	1.76	0.87	0.80	0.51

1. Values in table are Mean Absolute Differences between sensor and baseline temperature in Degrees Celsius
2. N/A represents test data not available. See test result section for more detailed explanation.

Throughout the fixed temperature testing, the Sprague sensor reported temperature variations significantly greater than the other sensors tested. On any given test, the Sprague sensors' raw data varied by 1.0 to 2.0° C while the other sensors varied by only 0.1 or 0.2° C. It is important to note that the Sprague sensor had a data resolution of 0.55° C while the other sensors reported resolution around 0.1° C. Averaging the Sprague sensor's raw data yielded an average error of 0.8° C for the fixed temperature tests. The graph on the left illustrates a typical in-pavement sensor's performance (in this case, Vaisala) while the performance of the Sprague sensor is provided on the right. The difference in data variation is shown in the graphs as well.



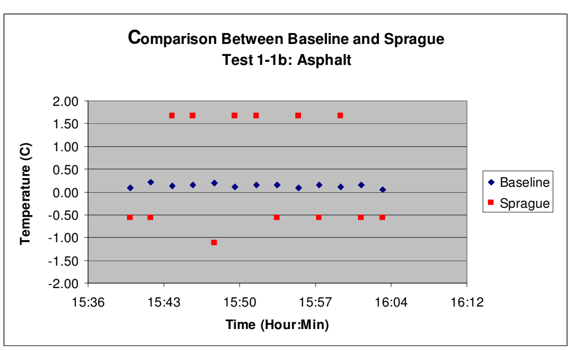


Test 1-1a: 5° C

For both the concrete and asphalt portions of the test, the individual baseline temperatures were constant, ranging between 4.4 and 4.8° C. The Aanderaa, Lufft, SSI, Vaisala and Control Products sensors reported mean absolute errors less than 0.5° C. On the concrete test, Boschung and Sprague reported mean absolute errors of 0.5° C or less and the Point Six reported a mean absolute error of 0.9° C. For the asphalt test, the Sprague sensor reported a mean absolute error of 0.8° C and the Boschung and Point Six reported mean absolute errors less than 1.9° C.

Test 1-1b: 0° C

For both the concrete and asphalt portions of the test, the individual baseline temperatures were constant, ranging between 0.0 and 0.5° C. The Aanderaa, Boschung, Lufft, SSI, Vaisala and Control Products sensors reported mean absolute errors less than 0.5° C. The Sprague sensor had significant temperature variation on this constant temperature test, reporting a 1.2 and 3.0° C variation on the concrete and asphalt tests respectively. The following graph is a sample.

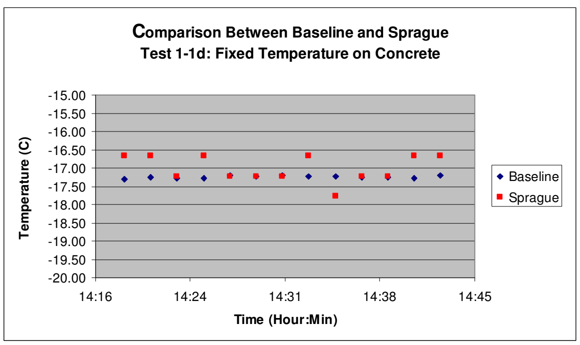


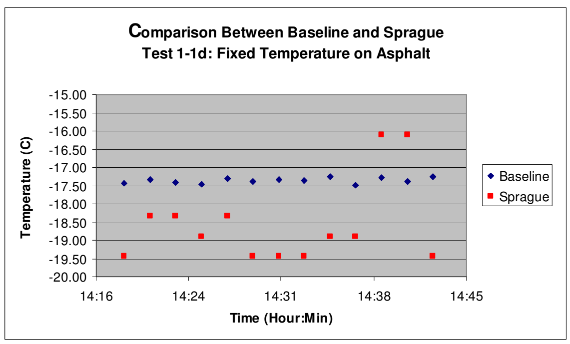
Test 1-1c: -6° C

For both the concrete and asphalt portions of the test, the individual baseline temperatures were constant, ranging between -4.5 and -6.7° C. The wide range of baseline temperatures indicated that the pavement test sections may not have been given enough time to fully acclimate to the test temperature before the data was collected. Despite this wide variation, the Lufft, Vaisala, Point Six and Boschung reported mean absolute errors less than 0.3° C. The Control Products, SSI and Aanderaa sensors reported mean absolute errors less than 0.6, 0.8 and 1.3° C, respectively. The Sprague reported mean absolute errors of 0.5 and 1.5° C on the concrete and asphalt tests respectively.

Test 1-1d: -17° C

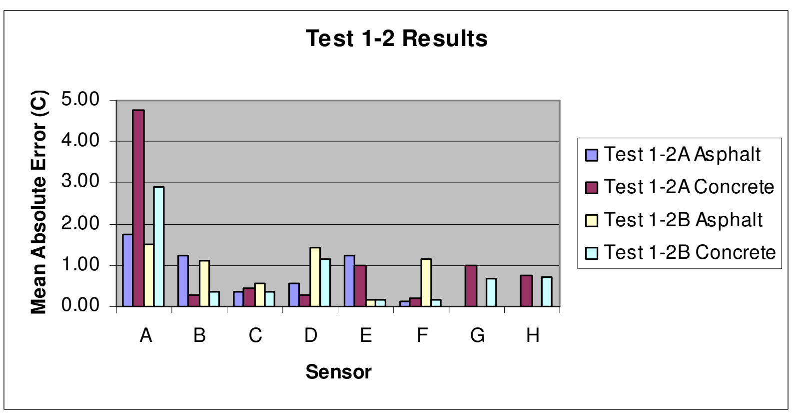
For both the concrete and asphalt portions of the test, the individual baseline temperatures were constant, ranging between -16.9 and -17.6° C. The Aanderaa, Boschung, Point Six and Vaisala reported mean absolute errors less than 0.3° C. It should be noted that the Point Six had six bad data points on the concrete test that were eliminated from the analysis. The Lufft and SSI reported mean absolute errors were less than 0.8° C. The Control Products sensor reported mean absolute errors of 1.2 and 0.3° C on the asphalt and concrete tests respectively. The Sprague reported a mean absolute error of 0.3° C on the concrete test. On the asphalt test the Sprague reported a wide variation in temperatures with values ranging from -16.0 to -19.5° C as shown in the following graphs.





4.2.2 Variable Temperature Tests

During the variable temperature tests, most of the sensors reported mean absolute errors less than 1.5° C. The average error was 0.9° C. During both asphalt tests, there was a data collection error in which the data captured from both mobile sensors (Control Products & Sprague) was the air temperature instead of the pavement temperature. The asphalt mobile sensor data was omitted from analysis.

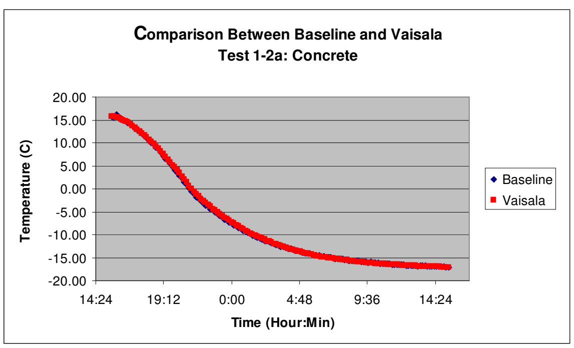


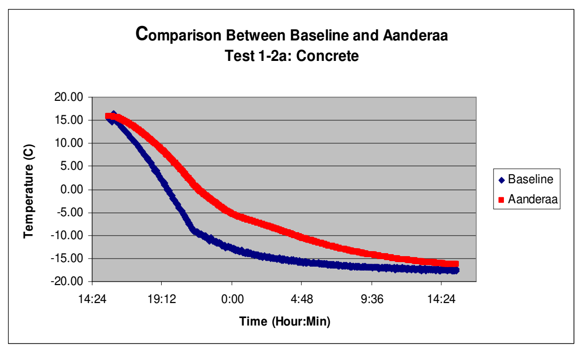
Test 1-2a: Declining Temperature

For both the concrete and asphalt portions of the test, the baseline temperatures smoothly transitioned from 16 to -17° C. The Lufft, Point Six and Vaisala sensors all reported mean absolute errors of 0.5° C or less. The Control Products and Sprague sensors reported mean absolute errors less than 1.0° C during the concrete test. The SSI and Boschung errors were less than 1.3° C. The Aanderaa reported mean absolute errors of 1.7 and 4.8° C on the asphalt and concrete tests respectively.

The following graphs are examples of typical sensor performance (left) and Aanderaa performance (right) on concrete. Because the baseline and sensor data for the graph on the right are so close, it is evident that the Vaisala sensor was very responsive to the changing temperature.

In contrast, the graph on the right shows that the Aanderaa sensor was slower to respond to the temperature change. This discrepancy is caused by the placement of the Aanderaa sensor's temperature sensing element. Because the sensing element is deeper in the pavement section, it does not respond as quickly to temperature change. Because the primary measure for sensor performance is the difference between subject sensors and baseline sensors attached to the surface of the pavement, these sensors appear to be in error during sudden changes in temperature. It is evident from the data at the end of the testing period that after the pavement section has stabilized the Aanderaa sensor reaches the stable temperature. Thus, while the Aanderaa sensor is accurate, the test simply shows that it does not respond as quickly as other sensors.





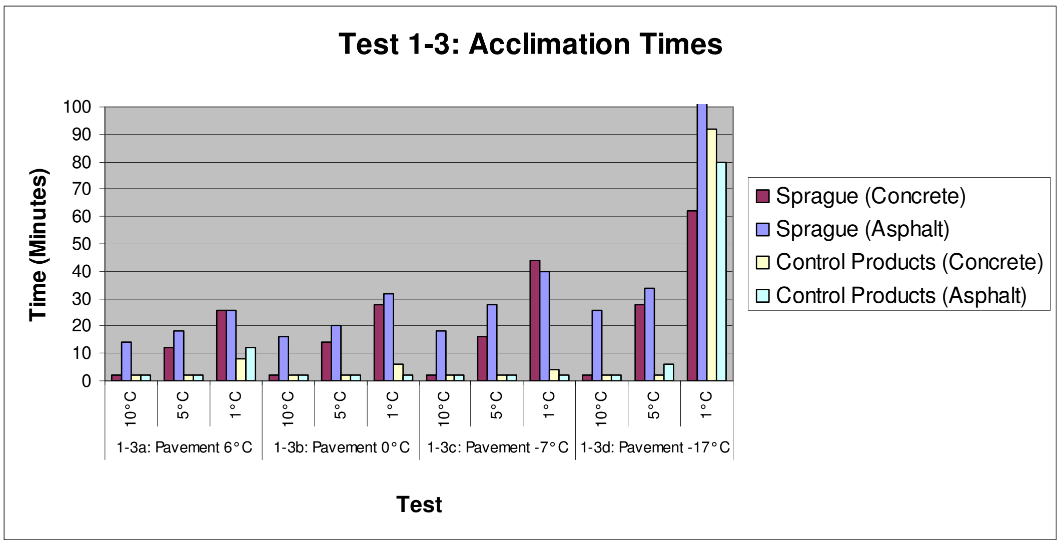
Test 1-2b: Increasing Temperature

For both the concrete and asphalt portions of the test, the baseline temperatures smoothly transitioned from -17 to 15° C. The Lufft and SSI reported mean absolute errors less than 0.6° C. The Control Products and Sprague sensors both reported mean absolute errors of 0.7° C during the concrete test. The Boschung, Point Six and Vaisala reported mean absolute errors less than 1.5° C. The Aanderaa reported mean absolute errors of 1.5 and 2.9° C on the asphalt and concrete tests respectively.

4.2.3 Mobile Sensor Acclimation Time

This test measured the time required for the mobile sensors to stabilize at a reading when moved from a warm to a cold environment. Acclimation time tests were conducted at four different temperatures (-17, -7, 0 and 6° C).

The approximate average acclimation times for the Control Products sensor were 2.5 and 20 minutes to achieve accuracy within 5 and 1° C respectively. The Sprague sensor consistently reported significantly longer acclimation times than the Control Products sensor, approximately 19 minutes longer to achieve accuracy within 1 and 5° C. Also, as might be expected, the greater the initial temperature contrast between the pavement and sensor, the greater the acclimation time. The graphs below present sample data and Table 6 presents the test data.



Test 1-3a: Time to Acclimate With Pavement at 6° C

During both the concrete and asphalt tests, the pavement test sections were a constant 5.6° C. The Control Products sensor responded the quickest to the temperature change, providing accuracy within 1.0° C after only 12 minutes of acclimation. The Sprague sensor took 26 minutes to respond to the same level of accuracy.

Test 1-3b: Time to Acclimate With Pavement at 0° C

The pavement test sections were a constant 0.1° C during both the concrete and asphalt tests. The Control Products sensor again responded the quickest to the temperature change, providing accuracy within 1.0° C of its final temperature after only six minutes of acclimation. The Sprague sensor took 32 minutes to respond to the same level of accuracy.

Table 6: Mobile Sensor Acclimation Time Summary

Concrete

TEST NO.	1-3a: Pavement 6° C			1-3b: Pavement 0° C			1-3c: Pavement -7° C			1-3d: Pavement -17° C		
	Minutes to report accuracy within:											
	10° C	5° C	1° C	10° C	5° C	1° C	10° C	5° C	1° C	10° C	5° C	1° C
Sprague	2	12	26	2	14	28	2	16	44	2	28	62
Control Products	2	2	8	2	2	6	2	2	4	2	2	92

Asphalt

TEST NO.	1-3a: Pavement 6° C			1-3b: Pavement 0° C			1-3c: Pavement -7° C			1-3d: Pavement -17° C		
	Minutes to report accuracy within:											
	10° C	5° C	1° C	10° C	5° C	1° C	10° C	5° C	1° C	10° C	5° C	1° C
Sprague	14	18	26	16	20	32	18	28	40	26	34	300
Control Products	2	2	12	2	2	2	2	2	2	2	6	80

Test Summary: Mean Absolute Error Values

TEST NO.	1-3a Pavement 6° C		1-3b Pavement 0° C		1-3c Pavement -7° C		1-3d Pavement -17° C	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
Sprague	1.76	1.01	2.30	1.18	2.35	1.44	3.55	1.66
Control Products	0.40	0.37	0.43	0.47	0.80	0.57	1.15	0.86

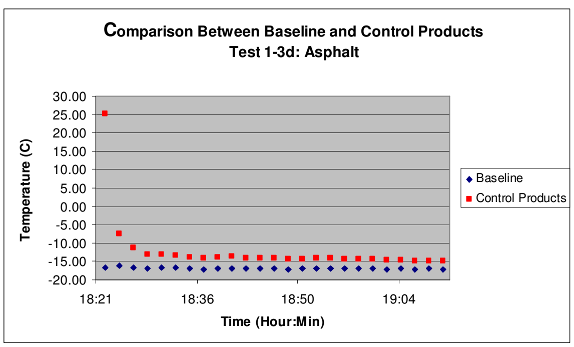
*Test Summary values are calculated using the data from the entire test duration (3-5 hours)

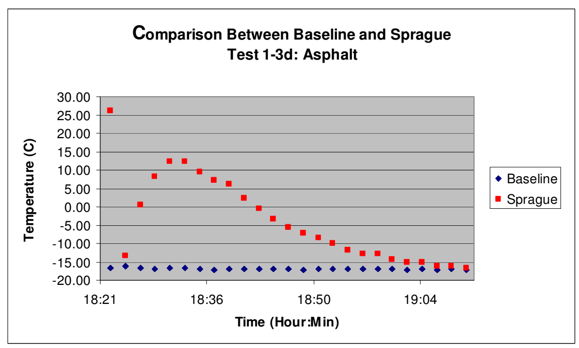
Test 1-3c: Time to Acclimate With Pavement at -7° C

During the concrete and asphalt tests, the pavement test sections were a constant -7.1 and -6.3° C respectively. The Control Products sensor responded the quickest to the temperature change, providing accuracy within 1.0° C of its final temperature after only four minutes of acclimation. The Sprague sensor took 44 minutes to respond to the same level of accuracy.

Test 1-3d: Time to Acclimate With Pavement at -17° C

During the concrete and asphalt tests, the pavement test sections were a constant -17.5 and -17.1° C, respectively. The times required to acclimate to within 1.0° C were significantly longer for this test, presumably due to the colder temperature. The Control Products sensor acclimated the quickest to 5.0° C accuracy within six minutes and then to within 1.0° C accuracy after an average of 86 minutes. The Sprague sensor over concrete acclimated to within 5.0 and 1.0° C accuracy after 34 and 62 minutes. During the five-hour asphalt test, the Sprague sensor never reached accuracy within 1.0° C.





4.2.4 Varied Mobile Sensor Height

This test was conducted with the mobile sensors mounted at varying heights. Table 7 presents the summarized results. Overall, the Control Products sensor provided the most accurate, consistent and precise data with an average mean absolute error of 0.31° C, while the Sprague reported 0.72° C. The average error for sensors over asphalt was 0.71° C while the average error over concrete was 0.32° C.

The Sprague sensor produced highly variable raw data and often ranged up to 1.5° C per test. A standard deviation test was performed to confirm this; the Sprague sensor reported a standard deviation five times higher than the Control Products (0.10 compared to 0.52). It is necessary to note that some of the Sprague's variability is due to its 0.55° C data resolution (the Control Products sensor has data resolution of 0.1° C). While the Sprague sensor reported high variability in its raw data, averaging the raw data yielded significantly more accurate results, often within 0.5° C of its baseline sensor. Across all temperatures, mounting heights and pavement types, the Sprague sensor had an average error of 0.72° C. The following graphs provide a comparison of the Control Products temperature (left) and the Sprague variability (right).

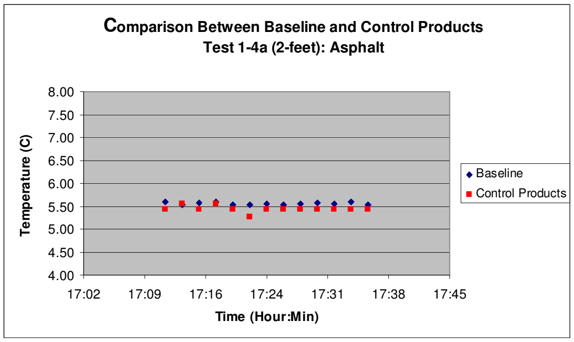
Table 7: Varied Mobile Sensor Height Summary

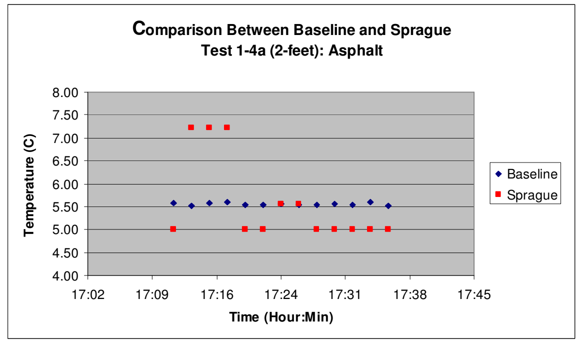
Temperature	Sensor	Mounting Height 1 foot Asphalt	1 foot Concrete	2 feet Asphalt	2 feet Concrete	3 feet Asphalt	3 feet Concrete	4 feet Asphalt	4 feet Concrete	Average By Sensor	Average of Both Sensors
6° C	Sprague	0.73	0.46	0.72	0.35	0.61	0.30	0.79	0.47	0.55	0.34
	Control Products	0.12	0.15	0.12	0.16	0.12	0.07	0.06	0.15	0.12	
0° C	Sprague	1.27	0.41	0.86	0.29	1.02	0.32	1.13	0.34	0.71	0.40
	Control Products	0.06	0.14	0.08	0.15	0.11	0.06	0.08	0.09	0.10	
-5° C	Sprague	0.81	0.41	0.90	0.23	0.84	0.29	1.53	0.46	0.68	0.50
	Control Products	0.37	0.14	0.37	0.10	0.46	0.19	0.55	0.30	0.31	
-17° C	Sprague	1.44	0.22	1.37	0.59	1.71	0.33	1.56	0.31	0.94	0.83
	Control Products	1.27	0.43	0.56	0.56	0.55	1.53	0.54	0.32	0.72	
Summary	Sprague	1.06	0.38	0.96	0.37	1.05	0.31	1.25	0.40	0.72	N/A
	Control Products	0.46	0.22	0.28	0.24	0.31	0.46	0.31	0.22	0.31	N/A
	Both Sensors	0.76	0.30	0.62	0.30	0.68	0.39	0.78	0.31	N/A	0.52

* Values in table are mean absolute differences between sensor and baseline temperature in degrees Celsius.

* Average of standard deviations of baseline/sensor difference for Control Products sensors were 0.07° C and 0.13° C for asphalt and concrete respectively.

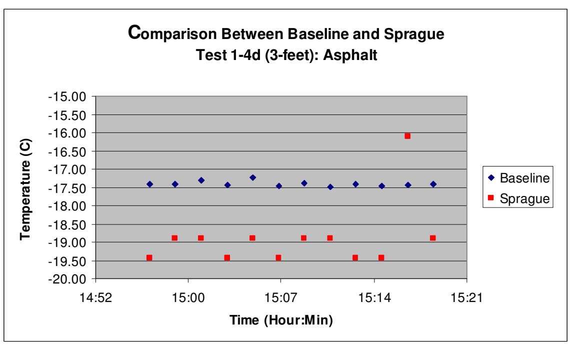
* Average of standard deviations of baseline/sensor difference for Sprague sensors were 0.71° C and 0.33° C for asphalt and concrete respectively.

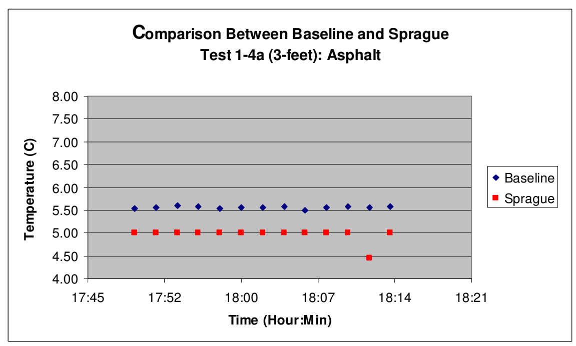




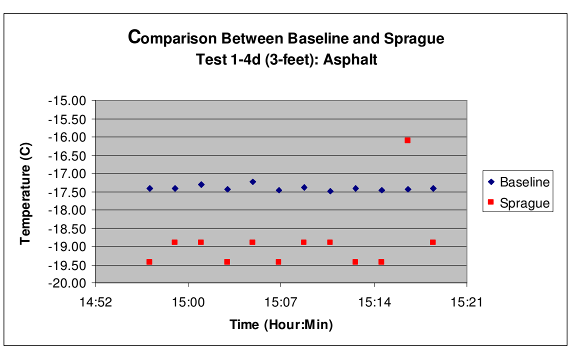
The test results indicated that a sensor installation height of up to four feet had a negligible effect on sensor performance. Average mean absolute errors varied by less than 0.1° C by height classification. It should be noted that only the Sprague manufacturer specified that their sensor be installed a minimum of 20 inches above the pavement surface. The Control Products manufacturer stated that installation height did not affect their sensor's accuracy.

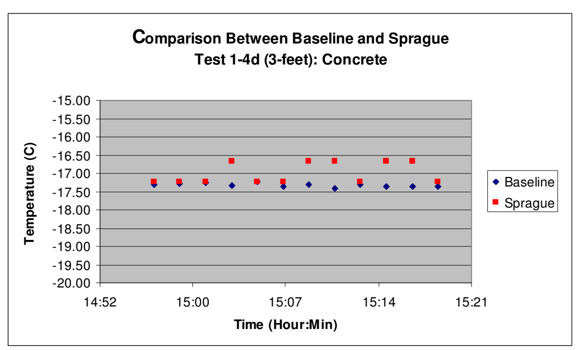
Inspection of the combined Control Products and Sprague data suggested that mobile sensor accuracy increased as the test temperature increased. The averages of the mean absolute errors decreased from 0.83 to 0.34 as the test temperatures increased from -17 to +6° C. A sample accuracy comparison is presented below. The -17° C test is on the left and the +6° C test is on the right.





Inspection of the combined data also suggested that the concrete tests yielded more accurate results than the asphalt. The averages of mean absolute errors for the concrete and asphalt tests were 0.32° C and 0.71° C respectively. This result is consistent with other mobile sensor tests that were conducted. See the raw data graph below for an example (the left graph is asphalt and the right is concrete).





Test 1-4a: Varied Mobile Sensor Height at 6° C

All tests were performed at a constant 5.6° C. For each test, the Control Products sensor displayed linear and consistent data. The Control Products sensor reported an average mean absolute error of 0.1° C. The Sprague data was significantly more sporadic, often showing a 1.0 or 1.5° C range of values. Averaging the sporadic raw data yielded more accurate results, averaging only 0.32° C of mean error per test.

Test 1-4b: Varied Mobile Sensor Height at 0° C

All tests were performed at constant temperatures between 0.0 and 0.4° C. The Control Products sensor performed consistently with an average mean absolute error of 0.1° C. The Sprague sensor performed sporadically during the asphalt testing (3.0° C range of values) and less so during the concrete tests (1.0° C range of values). Averaging the sporadic raw data yielded average mean errors of less than 0.5° C.

Test 1-4c: Varied Mobile Sensor Height at -5° C

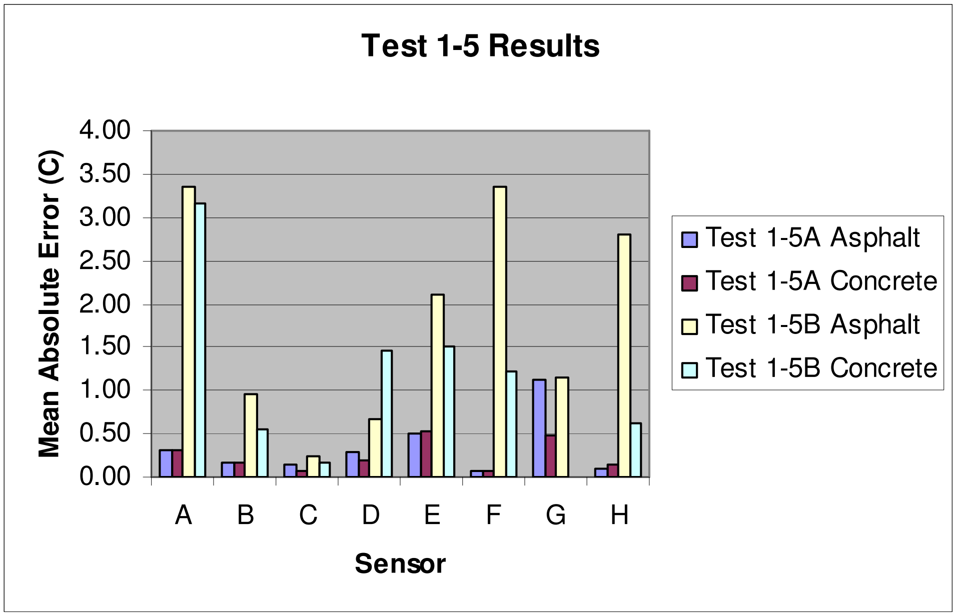
The asphalt tests were performed between -5.3 and -5.6° C, and the concrete tests were performed between -5.9 and -6.1° C. The Control Products sensor performed consistently with an average mean absolute error of 0.3° C. The Sprague sensor showed sporadic temperature variations of around 1.0° C for each test. Again, averaging the sporadic raw data yielded average mean errors of approximately 0.6° C.

Test 1-4d: Varied Mobile Sensor Height at -17° C

All tests were performed at constant temperatures between -17.2 and -17.5° C. The Control Products sensor performed consistently with an average mean absolute error of 0.7° C. The Sprague sensor performed significantly better on the concrete than on the asphalt tests. During the concrete tests, individual data points generally had a 0.5° C range, with average errors less than 0.6° C. During the concrete tests, individual data points generally had a 1.0° C range, with average errors of less than 1.5° C.

4.2.5 Cold Day With and Without Direct Solar Impact

Without direct solar impact (Test 1-5a), the average mean absolute error was 0.3° C. However, with direct solar impact (Test 1-5b), results varied with several sensors reporting errors greater than 1.0° C. The average mean absolute error for Test 1-5b was 1.6° C. Apparently, each sensor reacted differently to direct solar exposure of Test 1-5b. Since the sensors had significantly lower errors without solar impact (Test 1-5a) and in Test 1-2b (increasing temperature test), the direct solar heating of the pavement surface is likely the cause of the varied readings. Both the precise depth of each sensor's temperature "sensing element" and an uneven distribution of heat from the lamp could have caused the varied results from this test. The key finding from this test is that the addition of a heat source makes the baseline surface temperature deviate from the sensor's measured temperature more than if there was no additional heat source.

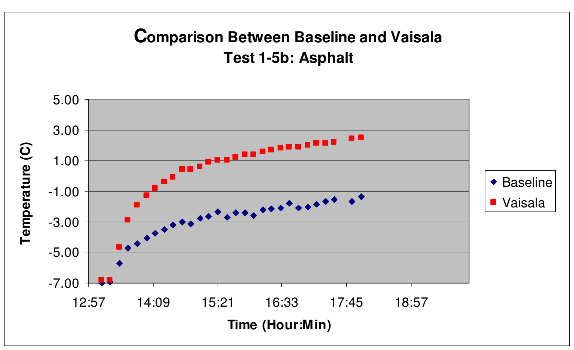


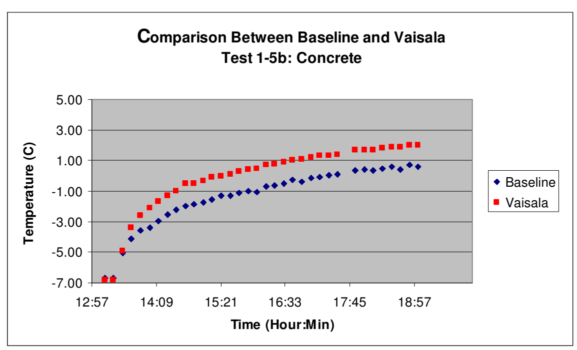
Test 1-5a: Without Direct Solar Impact

The tests were performed at constant temperatures between -6.7° and -7.5° C. Except for the Sprague sensor during the asphalt test, all of the sensors performed within 0.6° C of their respective baseline sensors. During the asphalt test, the Sprague's raw data had a wide variation, ranging from -8.5 to -5.0° C. Sprague's mean absolute error was 1.1° C for the asphalt test. When directly averaged however, the Sprague data showed a 0.6° C error. The Vaisala sensor only reported three readings during the 25-minute test period.

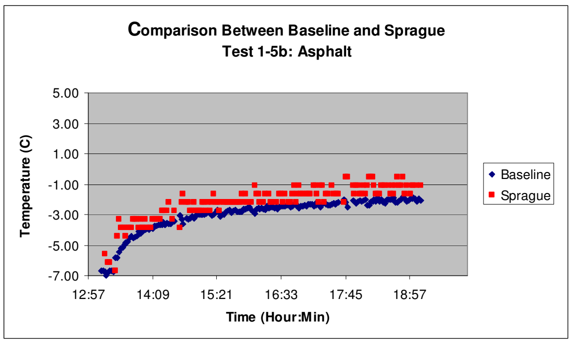
Test 1-5b: With Direct Solar Impact

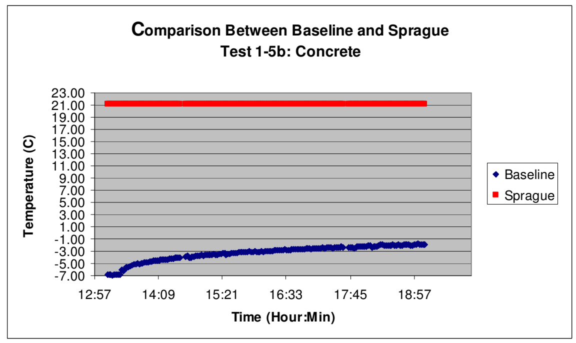
Pavement temperatures (baseline readings) increased from -7.0° to around 0.0° C during the test. It would appear that the pavement was not evenly heated by the "solar source" due to a wide variation in the final baseline temperatures, which were between -3° and +3° C. Furthermore, the wide variation in subject sensor performance would suggest that the subject sensors were impacted unevenly and/or responded to the solar impact differently. The following graphs illustrate the variation in baseline and subject sensor readings.





The Lufft and Boschung sensors most closely followed their respective baselines with mean absolute errors less than 1.0° C. The SSI and Point Six sensors reported mean absolute errors less than 2.1° C. The Vaisala reported mean absolute errors of 3.4 and 1.2° C on the asphalt and concrete tests respectively. The Aanderaa reported mean absolute errors less than 3.4° C. The Control Products sensor reported a mean absolute error of 0.6° C on the concrete test and a 2.8° C mean absolute error on the asphalt test. On asphalt, the Sprague sensor had a mean error of 1.15° C. However, the Sprague had a malfunction during the concrete test, reporting a constant reading of 21.1° C (70° F). The cause of the Sprague malfunction is unknown, but it is possible that the sensor was erroneously reporting the ambient temperature from hours earlier; the 21° C reading corresponds to the temperature at which the sensor was stored at prior to the testing. The following graphs show Sprague data on asphalt and concrete.



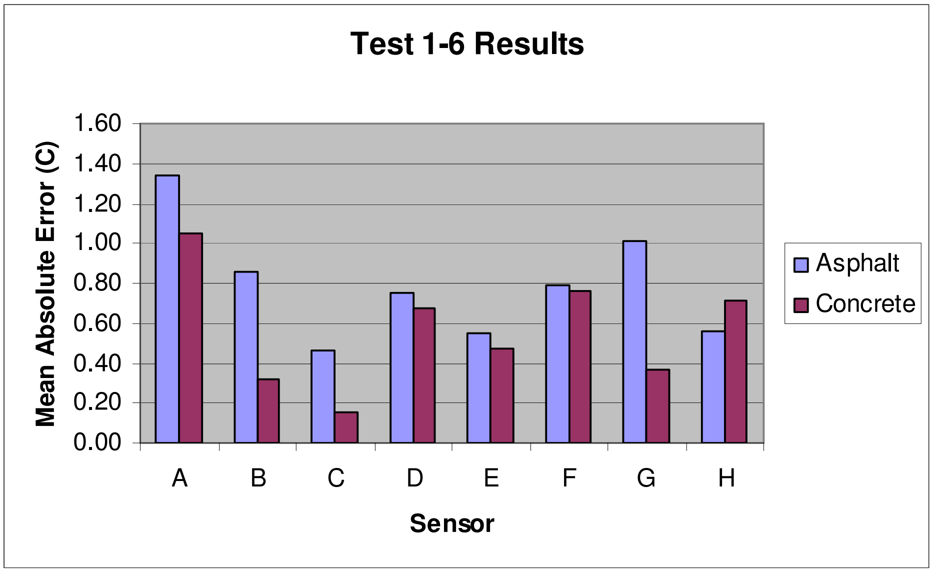


Solar radiation is difficult to reproduce in a laboratory environment. One of the factors that led to the relatively greater errors found in this test might be uneven heating by the lamps. In field deployments, the sun heats sensors and the pavement that surrounds them far more evenly. In the laboratory, the lamps were mounted asymmetrically over the pavement slabs. Even a small difference in distance between the lamp and sensor and the lamp and baseline could affect the temperature. Also, the way the light or heat reflected off the surface of the pavement is likely to have affected temperature inconsistencies in this test.

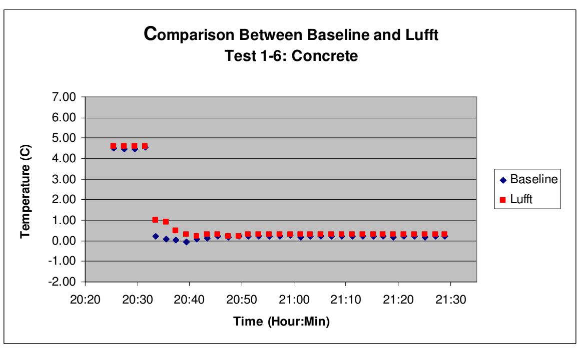
Also, this test compared the pavement sensors during a warming period. Initially, the subject sensors and baselines were at the same temperature and were warmed. The temperatures generally immediately diverged as either the baseline or subject sensor reported a warmer condition. The test was not run long enough to see whether the baseline and pavement sensor temperatures would converge when the temperatures in the pavement sections had reached temperature equilibrium.

4.2.6 Test 1-6: Warm Pavement With Snowfall

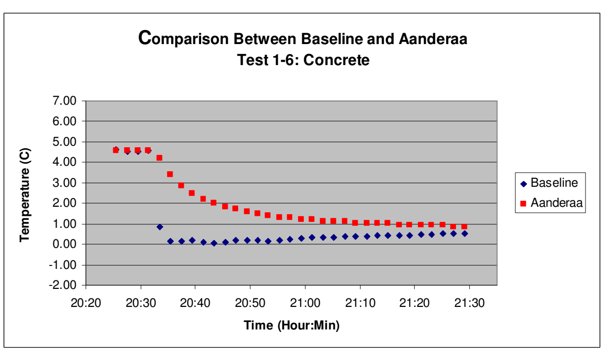
This test was conducted to determine the effects of the situation where recently fallen snow melts when it contacts the pavement. The initial stabilized pavement temperature was 4.6° C. After the application of snow, the pavement underwent a rapid temperature drop, and the pavement stabilized at 0° C. The baseline sensors reported the duration of this 4.6° C temperature drop to be less than two minutes.



The Lufft and SSI sensors reported the temperature drop in less than four minutes and reported mean absolute errors less than 0.6° C. The following graph notes the quick response time of the Lufft sensor.



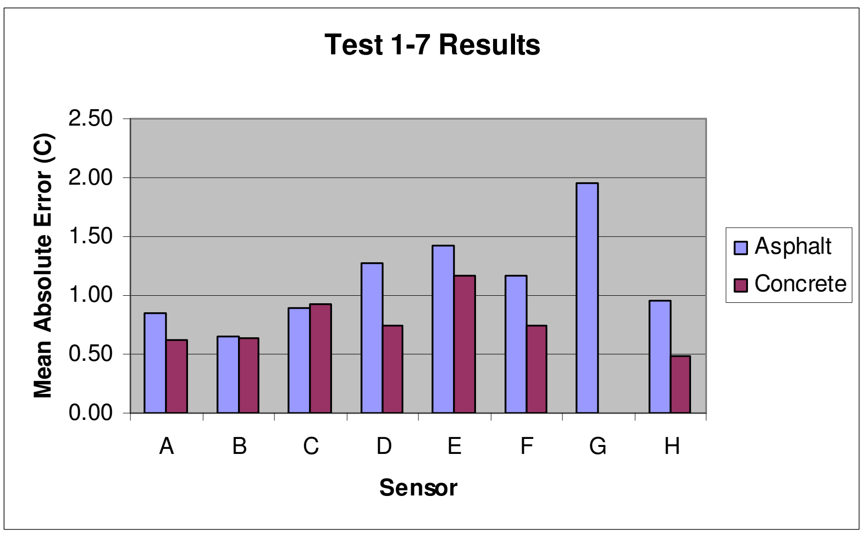
The Boschung, Vaisala and Control Products sensors also responded to the temperature drop in less than four minutes and reported mean absolute errors of less than 0.9° C. The Sprague sensor responded to the temperature drop in less than four minutes and had mean absolute errors of 0.4 and 1.0 for the concrete and asphalt tests respectively. The Aanderaa took almost 30 minutes to report within 1.0° C of the final temperature and had a mean absolute error less than 1.4° C. Aanderaa's longer acclimation time is shown in the following graph.



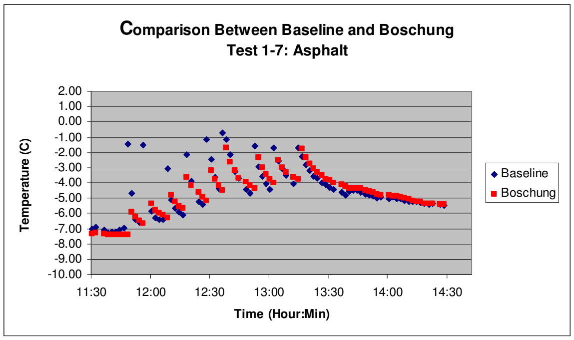
The Point Six sensor fully responded to the temperature drop after 20 minutes, but the final temperature was almost 1.0° C below the baseline on the asphalt test. Point Six's mean absolute errors were less than 0.8° C.

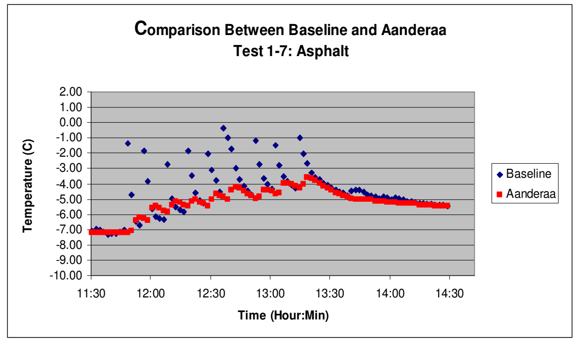
4.2.7 Test 1-7: Cold Pavement With Rainfall

For the cold pavement with rainfall test, the initial pavement temperature was a steady -7.2° C. During the rainfall event (approximately 60 minutes in duration), the baseline temperatures rose 3° or 4° C and varied erratically between the initial -7.2° and 0.0° C. The erratic readings were due to the simulated rainfall event where the water (being warmer than the pavement) was incrementally sprayed onto the pavement. Because the baseline sensors were affixed to the pavement surface, they responded to the incremental spraying. The warmer water would contact the pavement (and sensor) then cool to the pavement temperature each time that the pavement was sprayed with water. After the rain event, the baseline temperatures dropped approximately 2° C and then stabilized at -5.5° C.

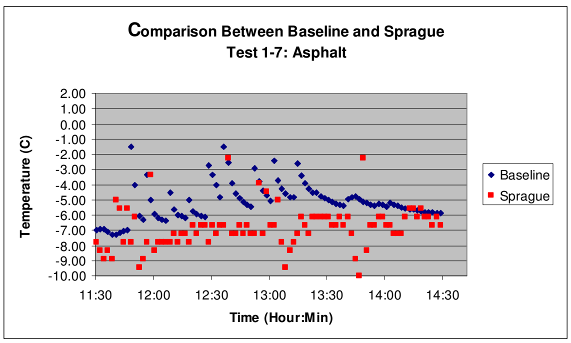


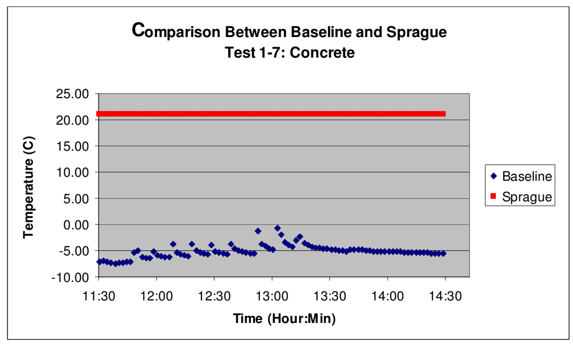
During this test, the Aanderaa, Boschung, Lufft and Control Products sensors reported mean absolute errors of 1.0° C or less. The Point Six, SSI and Vaisala reported mean absolute errors of 1.4° C or less. It should be noted that data for the Point Six and Aanderaa did not show the erratic variation that the baseline sensors did during the rain event. In this case, the Point Six and Aanderaa actually provided more consistent pavement temperature data during the rain event than the baseline sensors did. A graphical comparison is presented below; on the left, the baseline and subject sensor report temperature variations as the rain contacts the pavement during the rain event are shown. On the right, the subject senor does not report the same temperature variations as the baseline.





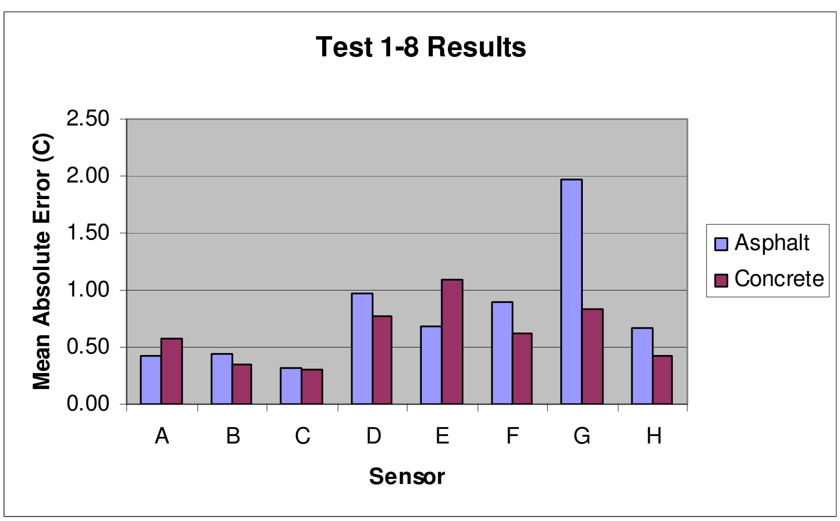
The Sprague sensor reported erratic and widely ranging data throughout the asphalt segment of the test. Averaging the erratic asphalt data resulted in a mean error of 1.7° C. During the concrete portion of the test, the Sprague sensor failed and reported a steady value of 21.1° C. See below for graphs of the Sprague sensor.



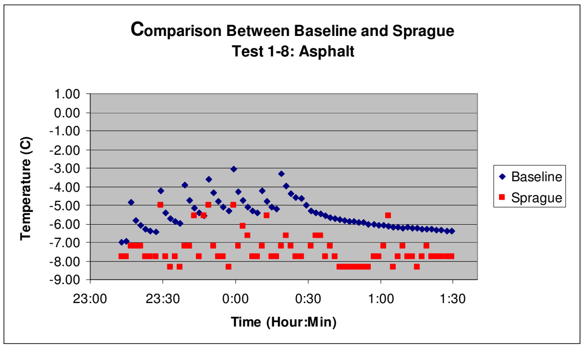


4.2.8 Test 1-8: Iced Pavement With Rainfall

For the iced pavement with rainfall test, the initial pavement temperature was a steady -7.0° C. During the rainfall event (approximately 60 minutes in duration), the baseline temperatures rose 3° or 4° C and varied erratically between the initial -7.0° and 1.0° C. Again, the erratic variation was due to the simulated rainfall application. After the rain event, the baseline temperatures dropped to 2° C and then stabilized between -6.5° and -7.0° C as ice formed on the pavement.

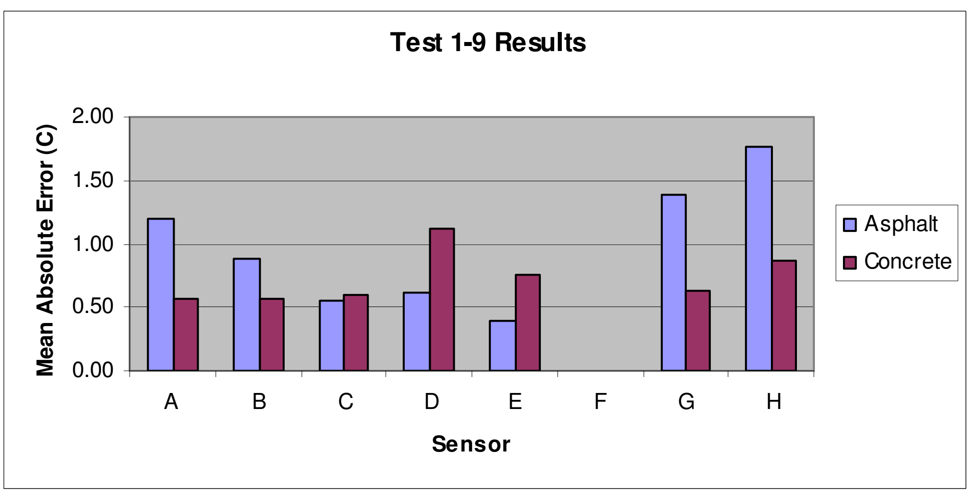


The results from this test were very similar to the results from the previous test (Test 1-7 Cold Pavement with Rainfall). The Aanderaa, Boschung, Lufft and Control Products followed their baseline sensors with mean absolute errors less than 0.7° C. The Point Six, SSI and Vaisala reported mean absolute errors less than 1.1° C. The Point Six and Aanderaa sensors lacked the erratic variation of the other sensors during the rain event which was probably because their temperature sensing elements are further below the surface.



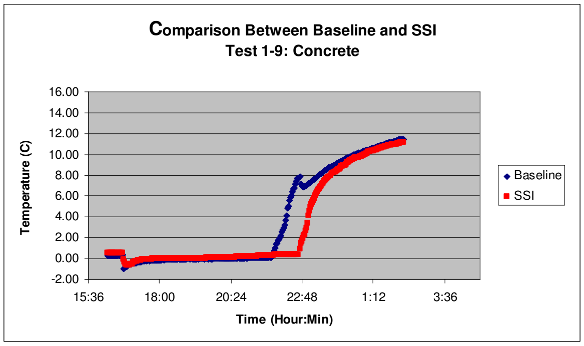
4.2.9 Test 1-9: Compacted Snow (Melting)

For the compacted snow test, the initial pavement temperature was 0.3° C. When the snow was applied, the pavement temperature dropped to around -1.0° C and then slowly rose over the next 10 to 20 minutes, steadying at 0.0° C. After the snow finally melted, the pavement temperature rapidly increased 5° to 10° C during the next 45 minutes. After the 45-minute rapid rise, the rate of temperature increase slowed until the test was ended. At the conclusion of the test, the baseline sensors reported temperatures between 10 and 14° C.



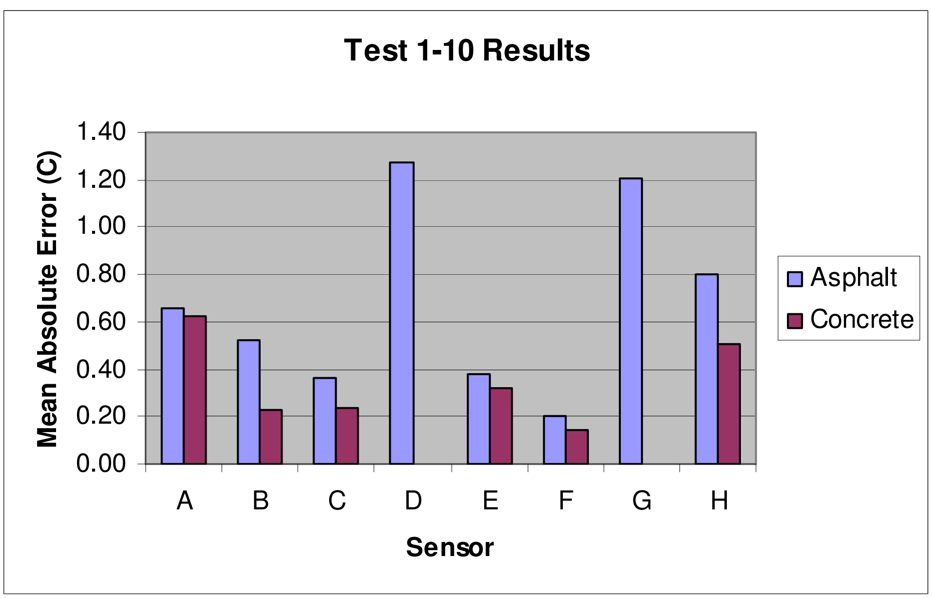
During this test, the Boschung, Lufft and SSI reported mean absolute errors less than 0.9° C. The Aanderaa and Point Six sensors reported mean absolute errors of 1.2° C or less. The mobile sensors, Control Products and Sprague, reported mean absolute errors less than 1.8° C.

The Lufft sensor data during the rapid temperature increase was missing for the concrete test. The Point Six reported no data during several portions of the concrete test. The Boschung and SSI sensors had 30- to 60-minute delays in reporting the rapid temperature increase, as shown in the following graph. The Vaisala's data collection computer malfunctioned during the test and reported no data. Both mobile sensors performed significantly better during the asphalt testing.

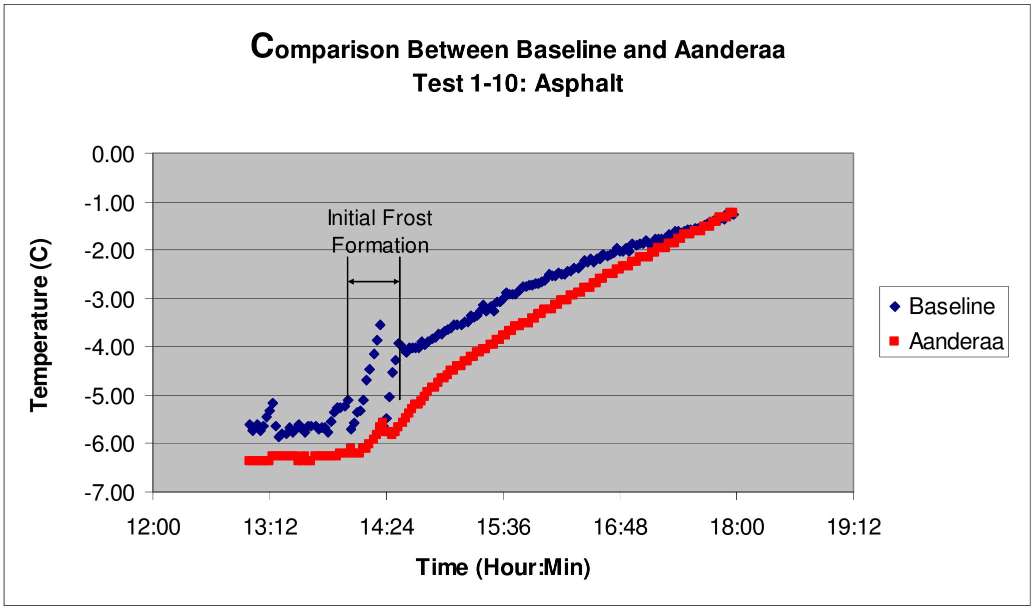


4.2.10 Test 1-10: Frost Depositing

Frost formation on a pavement's surface greatly affects the temperature of the top of the pavement surface and affects temperature below the surface to a lesser extent. The initial baseline temperatures for this test were between -5.5° and -6.5° C. Approximately 60 minutes after the test begun, frost began to form on the pavement. At that point, the baseline sensors recorded a temperature spike followed by increasing readings.



Three hours later the baseline pavement temperatures had risen to approximately -1.0° C, see below for a sample Aanderaa graph (note the baseline temperature spike just before 14:24). It is assumed that the temperature increase during the test was due to the warm water that was placed in the test chamber to facilitate frost formation.



The Lufft, SSI and Vaisala reported mean absolute errors less than 0.4° C. The Aanderaa, Boschung and Control Products sensors had mean absolute errors of 0.8° C or less. The Point Six sensor failed to output usable data for the concrete test and reported a mean error of -1.3° C during the asphalt test. The Sprague sensor reported a mean absolute error of 1.2° C for the asphalt test. The Sprague sensor failed during the concrete tests, displaying a constant 21.1° C for the duration of the test.

4.2.11 Test 1-11: Mobile Sensor Performance in Varying Ambient Temperature

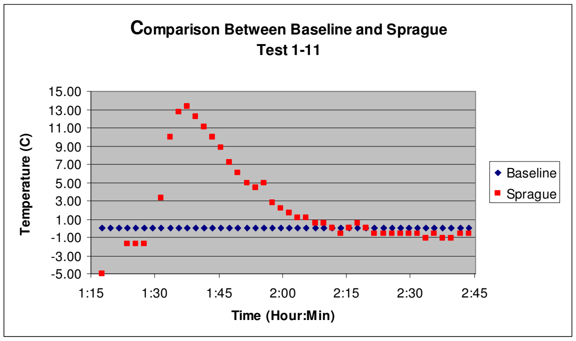
This test was conducted similar to Test 1-3 Mobile Sensor Acclimation Times". Similar results were yielded. First, the mobile sensors (Sprague and Control Products) were acclimated to an ambient temperature of approximately 18° C while aimed at an ice bath. Next, the sensors were brought into the test chamber where the ambient and target temperatures were 0.0° C. During this transition, the sensors remained aimed at the ice bath in order to isolate the effect that varying ambient air temperature has on mobile sensor performance. Test results are summarized in Table 8.

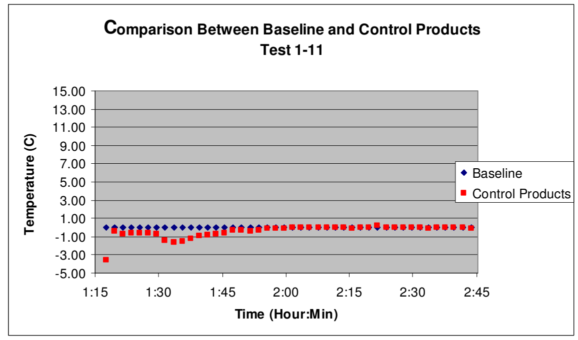
Table 8: Test 1-11 Summary

Sensor	Mean Difference (°C)	Mean Absolute Difference (°C)	Root Mean Square Difference (°C)
Sprague	3.81	4.68	7.90
Control Products	-0.40	0.40	0.77

During the initial room temperature portion of the test, the Sprague sensor, aimed at an ice bath, reported a reading of -1.5° C. When the Sprague was moved into the test chamber, the readings rapidly rose to 13.0° C. After the temperature increase, the reading declined over the following 30 minutes, back down to the baseline of 0.0° C. The sensor characteristics for this test were similar to those shown in Test 1-3. The Sprague's mean absolute error was 4.7° C. The Sprague performance is shown below.

The Control Products sensor initially reported a temperature drop to -0.5° C and then leveled off to the baseline temperature of zero degrees Celsius, as shown below. These results suggest that the Sprague sensor is more influenced by varying ambient air temperature than the Control Products sensor.





4.3 Detailed Chemical Test Results

This section presents the results from the anti-icing chemical tests conducted in the laboratory. In these tests Sodium Chloride (NaCl) was chosen as the anti-icing chemical. Anti-icing chemicals were applied in accordance with WisDOT Guideline 35.25 (see Appendix C). Table 9 summarizes the results from the NaCl laboratory tests.

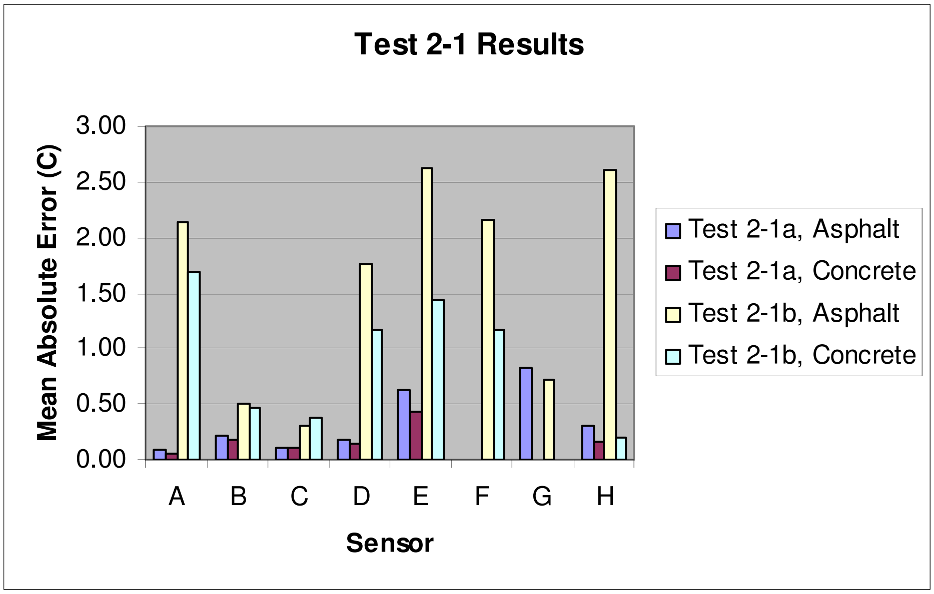
Table 9: Chemical Test Summary

Test Description:	NaCl: Cold Pavement w/o Solar Impact		NaCl: Cold Pavement w/ Solar Impact		NaCl: Warm Pavement w/ Snow		NaCl: Cold Pavement w/ Rainfall		NaCl: Iced Pavement w/ Rainfall	
TEST NO.	2-1a		2-1b		2-2		2-3		2-4	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.09	0.05	2.14	1.68	1.58	1.06	0.50	0.51	0.67	0.52
BOSCHUNG	0.22	0.18	0.51	0.46	0.28	0.63	0.37	0.26	0.45	0.26
LUFFT	0.10	0.10	0.31	0.37	1.10	0.28	0.60	0.59	N/A	N/A
POINT 6	0.18	0.14	1.76	1.17	0.72	0.57	1.08	0.56	1.34	0.74
SSI	0.62	0.43	2.62	1.44	0.44	0.51	0.68	0.77	1.10	0.97
VAISALA	N/A	N/A	2.15	1.16	0.71	0.60	0.34	0.48	0.38	0.54
SPRAGUE	0.82	N/A	0.71	N/A	0.94	N/A	1.27	N/A	2.02	N/A
CONTROL PRODUCTS	0.30	0.16	2.61	0.20	0.93	1.06	0.54	0.39	0.39	0.38

1. Values in table are Mean Absolute Differences between sensor and baseline temperature in Degrees Celsius
2. N/A represents test data not available. See test result section for more detailed explanation

4.3.1 Sodium Chloride – Cold Day With and Without Direct Solar Impact

The NaCl solar impact test produced results similar to the solar impact test without NaCl (Test 1-5b); both tests produced widely ranging baseline and subject sensor temperatures. It would appear that each sensor reacted differently to the solar impact simulator and that perhaps the solar simulator was not evenly distributing the solar radiation.

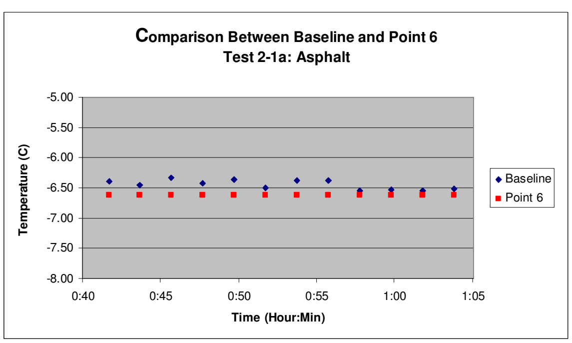


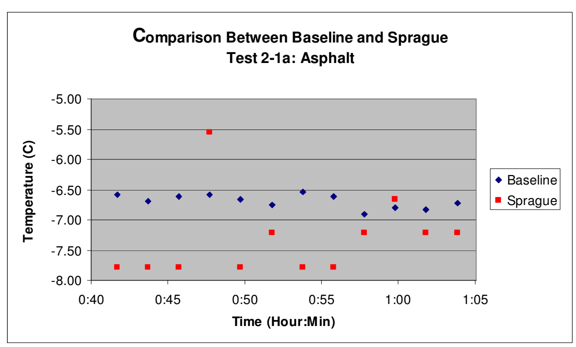
Test 2-1a: Without Direct Solar Impact

Prior to the start of this test, a NaCl mixture (application rate of 25 gallons per lane mile) was applied to the pavement and mobile sensors. The pavement temperature was constant during the 25-minute test, with individual baselines varying between 6.0° and 7.0° C.

The Aanderaa, Boschung, Lufft, Point Six and Control Products sensors reported mean absolute errors of 0.3° C or less. The SSI reported mean absolute errors or 0.6° C or less. The Sprague failed during the concrete test (reported a constant reading of 21.1° C) and reported a 2.5° C range of temperature values during the asphalt test. Sprague's mean absolute error was 1.2° C for the asphalt test. There was a data collection error in which the Vaisala data was not recorded.

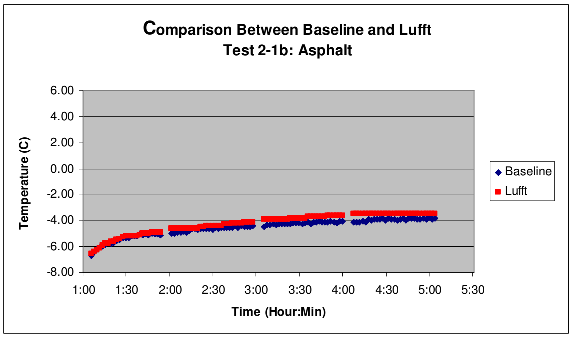
The two sample graphs below illustrate typical sensor performance (left) and the Sprague variability (right).

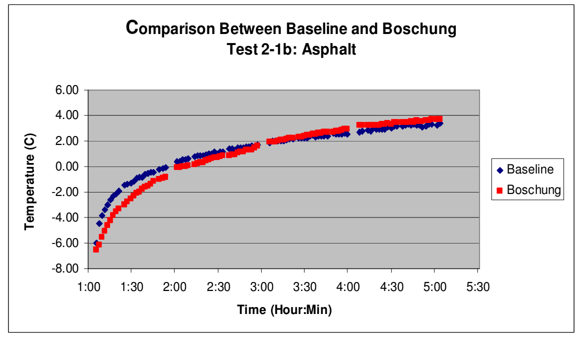




Test 2-1b: With Direct Solar Impact

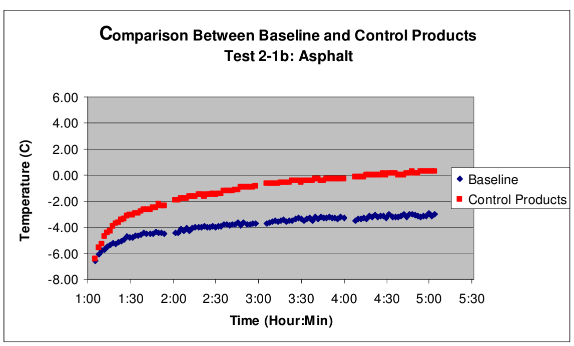
Test 2-1b immediately followed Test 2-1a. At 1:07 the sunlight simulator lights were switched on. Baseline temperatures rapidly rose during the next hour and continued to gradually rise until the end of the test. It should be noted that there was significant temperature variation between baseline sensors during this test. At the completion of the test, the baseline sensors varied between -4.0° and 4.0° C, see below. This wide variability in baseline readings is consistent with the results found without NaCl application (see Test 1-5b), suggesting that the pavements were not evenly heated by the "solar source."

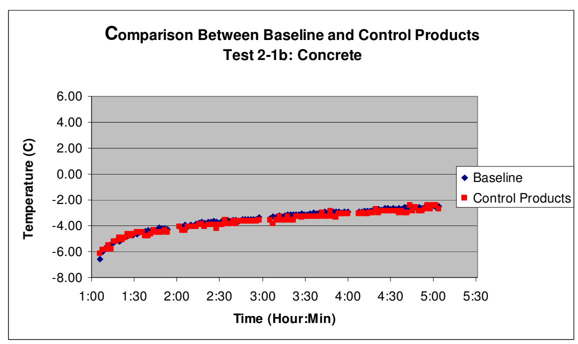




The Lufft and Boschung sensors followed their baselines, reporting mean absolute errors of 0.5° C or less. The Aanderaa, Point Six, SSI, Vaisala and Control Products also followed their baseline trends, but reported larger temperature errors with mean absolute errors between 1.2 and 2.6° C.

The Aanderaa, Point Six, SSI, Vaisala and Control Products sensors all performed significantly better during the concrete test than during the asphalt test. The averaged mean absolute errors were 1.1° C less during the concrete test. The following sample graphs illustrate this performance difference.

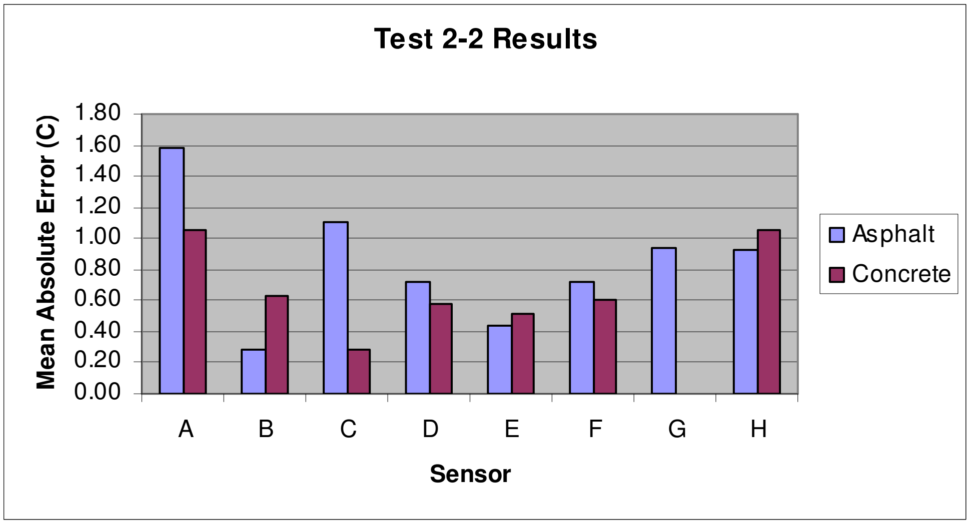




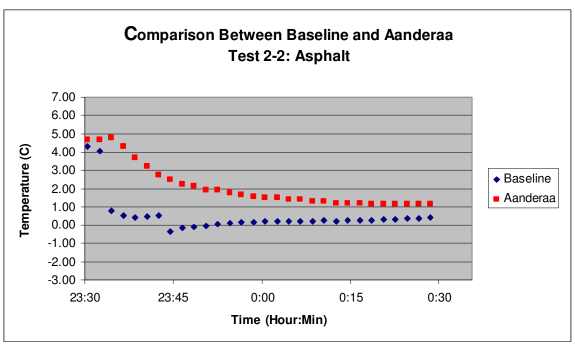
The Sprague failed during the concrete test (reported a constant temperature of 21.1° C) and reported a mean absolute error of 0.7° C during the asphalt test.

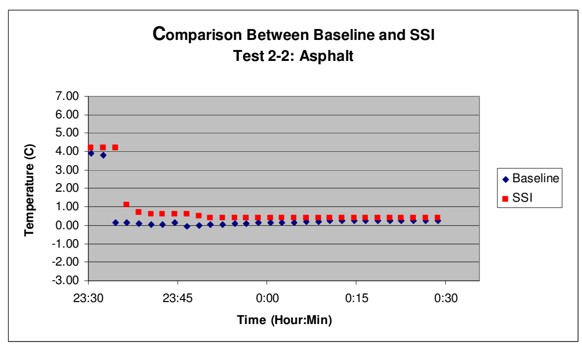
4.3.2 Test 2-2: Sodium Chloride – Warm Pavement With Snowfall

For this test, the initial pavement temperatures were between 4.0° and 5.0° C. Within approximately 5 minutes of the snowfall event, the pavement temperatures dropped to a constant 0.0° C.



The Boschung, Point Six and SSI sensors reported mean absolute errors of 0.7° C or less and responded to within 1.0° C of their baselines within 10 minutes or less. The Vaisala and Aanderaa sensors took longer to acclimate to their baselines, between 15 and 40 minutes. The Vaisala and Aanderaa reported averaged mean absolute errors of 0.7 and 1.3° C respectively for the asphalt and concrete tests. The variation in sensor acclimation time is show below, approximately 40 minutes on the left and four minutes on the right.



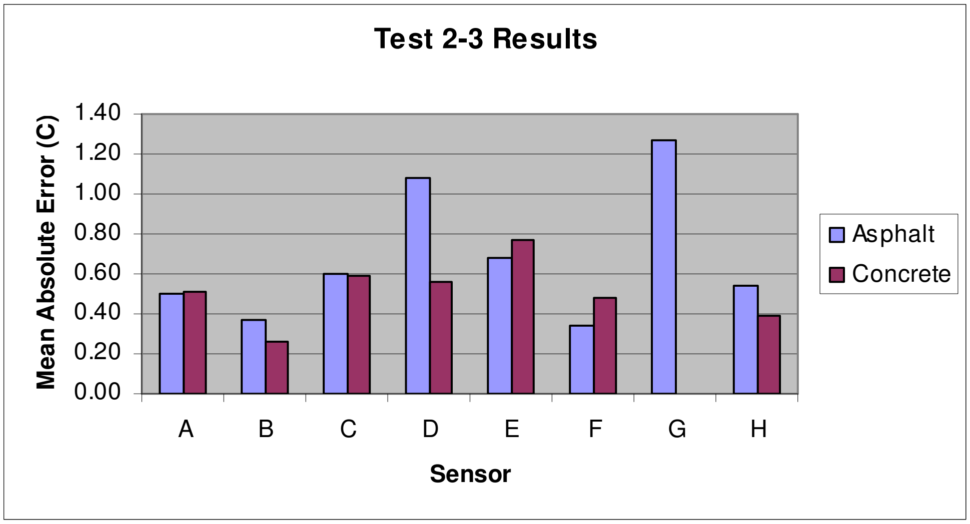


The Control Products sensor responded to the temperature drop within 10 minutes and reported mean absolute errors or 0.9 and 1.1° C for the asphalt and concrete test respectively.

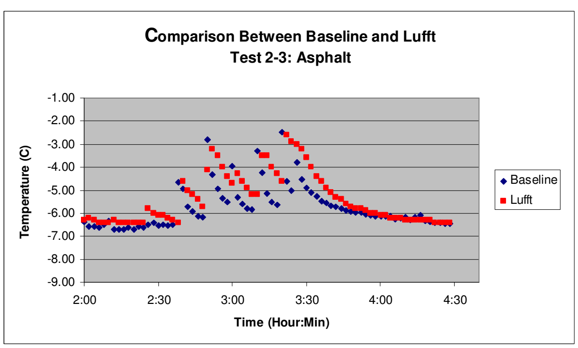
On the Asphalt test, the Sprague responded to the temperature drop within 10 minutes and reported a mean absolute error of 0.9° C. Averaging Sprague's raw temperature data yielded results within 0.2° C of its baseline for the asphalt test. The Sprague failed during the concrete test, reporting a constant 21.1° C. The findings from this test are consistent with the findings from the same test without NaCl (see Test 1-6).

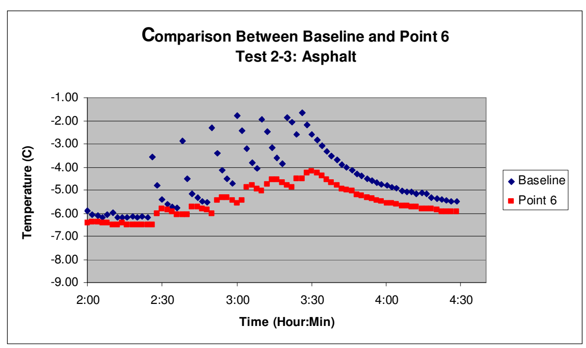
4.3.3 Test 2-3: Sodium Chloride – Cold Pavement With Rainfall

The initial pavement temperatures were between -6.0° and -6.5° C. During the approximate 70-minute rain event, baseline temperatures tended to increase several degrees, erratically varied between -6.0 and -1.0° C. The erratic temperature variations were due to the application of the simulated rain. Following the rain event, the baseline temperatures decreased and then leveled-off around the initial -6.5° C temperature. These test results do not differ significantly from the same test conducted without NaCl (see Test 1-7).

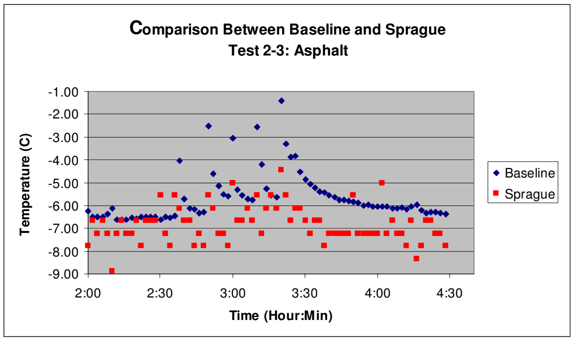


The Aanderaa, Boschung Lufft, Vaisala and Control Products sensors followed the baseline temperatures reporting mean absolute errors less of 0.6° C or less. Additionally, during the rain event, the Aanderaa and Point Six raw data did not have the erratic reading of the base sensor; the sensor data smoothly increased during the rain event. The Point Six and SSI sensors also followed their baselines with mean absolute errors less than 1.1° C. Shown below are examples of the baseline temperature variation during the rain event; note the Point Six has a smoother transition during the rain event.





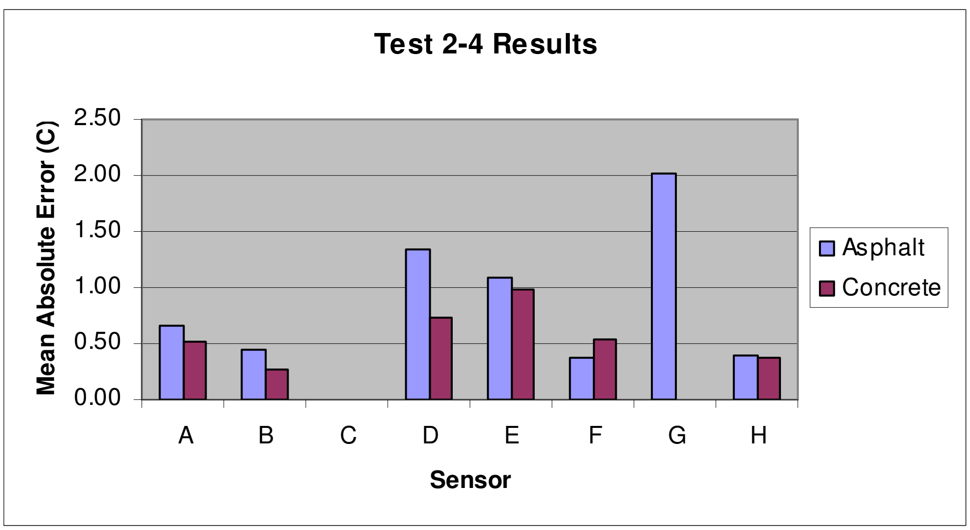
During the asphalt test, the Sprague sensor had significant temperature variation (between -5.0 and -9.0° C) and reported a mean absolute error of 1.3° C. The Sprague failed during the concrete test, displaying a constant 21.1° C. Shown below is an illustration of Sprague's variability.



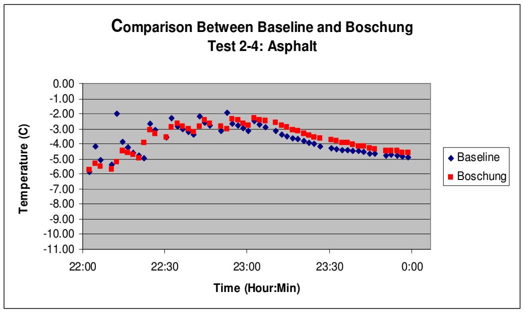
4.3.4 Test 2-4: Sodium Chloride – Iced Pavement With Rainfall

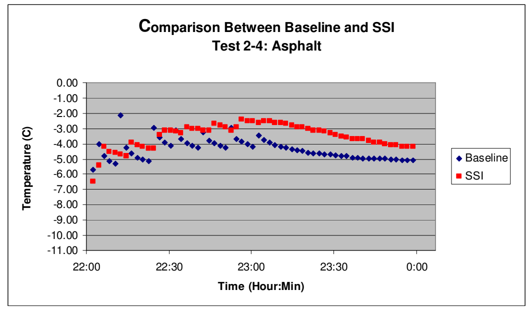
The initial pavement temperatures were between -5.0 and -6.0° C. During the approximate 70-minute rain event, baseline temperatures tended to increase several degrees, erratically varying between -6 and -1° C. Again the erratic temperature variations were due to the application of the simulated rain. Following the rain event, the baseline temperatures decreased and then leveled-off around the initial -5.5° C temperature. The findings from this test are consistent with the findings from the same test without NaCl (see Test 1-8).

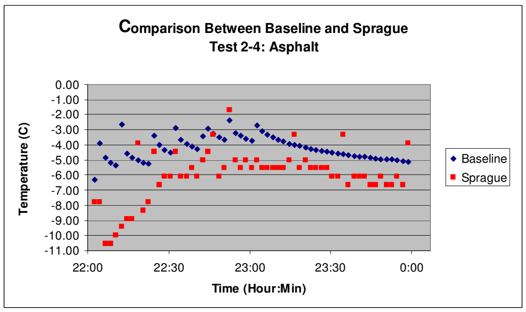
The Boschung, Vaisala and Control Products sensors followed their baseline sensors reporting mean absolute errors of 0.5° C or less; see below for a Boschung data graph. The Aanderaa reported mean absolute errors less than 0.7° C. The Point Six and SSI sensors reported mean absolute errors less than 1.4° C.

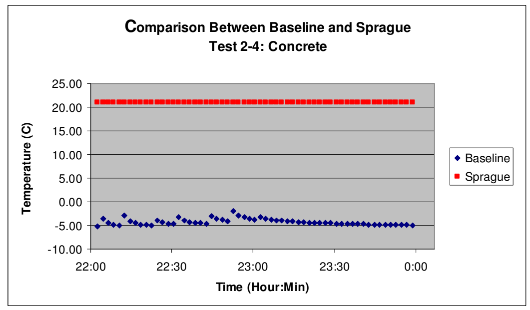


The SSI's temperature decrease seemed to be an hour delayed from its respective baseline sensor during both tests. A raw data graph is shown below. The Lufft sensor's data was lost because of a data collection error. During the asphalt test, that Sprague data was somewhat erratic, increasing from -11.0° C and then leveling off around -6.5° C; see below for a raw data graph. The mean absolute error for the Sprague during the asphalt test was 2.0° C. During the Concrete test the Sprague failed, reading a constant 21.1° C as shown below.









4.4 Detailed Field Test Results

This section presents the results from the field tests conducted at Mn/ROAD. Table 10 summarizes the field test results for the in-pavement sensors.

Table 10: Field Test Summary

Test Description:	**Cold Day w/ Solar Impact**		**Cold Day w/o Solar Impact**		**Cold Night w/o Radiation Cooling**		**Cold Night w/ Radiation Cooling**	
TEST NO.	**3-1a**		**3-1b**		**3-2a**		**3-2b**	
	Asphalt	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**
AANDERAA	0.39	1.66	N/A	N/A	0.09	0.17	0.44	0.39
BOSCHUNG	0.58	2.05	0.29	0.92	0.76	0.74	0.61	1.01
LUFFT	0.23	1.85	0.10	1.07	0.63	0.87	0.91	1.37
SSI	0.58	1.31	0.50	0.68	0.30	0.74	0.08	0.46
VAISALA	1.49	2.25	0.94	1.37	0.98	0.94	1.09	1.01

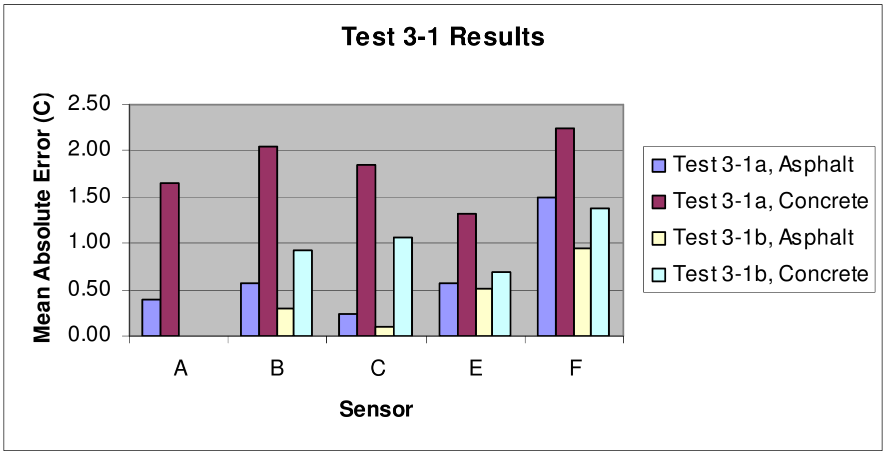
Test Description:	**Warm Pavement w/ Snowfall**		**Cold Pavement w/ Rainfall**		**Iced Pavement w/ Rainfall**	
TEST NO.	**3-3**		**3-4**		**3-5**	
	Asphalt	**Concrete**	**Asphalt**	**Concrete**	**Asphalt**	**Concrete**
AANDERAA	0.65	1.27	1.53	1.70	0.56	1.44
BOSCHUNG	0.80	0.49	2.03	1.34	0.35	0.76
LUFFT	0.53	0.37	1.73	1.43	0.40	1.20
SSI	0.37	0.70	2.47	2.51	0.69	1.40
VAISALA	1.28	2.75	1.50	1.59	2.42	0.63

1. Values in table are Mean Absolute Differences between sensor and baseline temperature in Degrees Celsius
2. N/A represents test data not available. See test result section for more detailed explanation

4.4.1 Field – Cold Day With and Without Direct Solar Impact

During both asphalt tests, the subject sensors closely followed their respective baselines. As was expected, the sunny day with solar impact test showed pavement temperatures increasing at a faster rate than during the cloudy day without solar impact.

During both concrete tests, the subject sensors generally reported greater temperature increases than their respective baselines. This temperature discrepancy was more pronounced during the test with solar impact.



Test 3-1a: With Direct Solar Impact

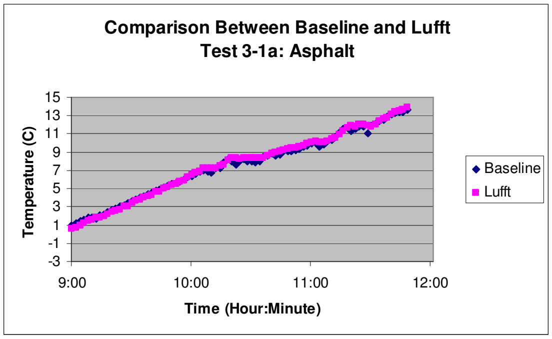
This test was conducted on a sunny morning between 9:00 and 11:50 a.m. The average wind speed was 7.7 miles per hour, and the ambient air temperature increased from -7.1° to -4.2° C during the test period.

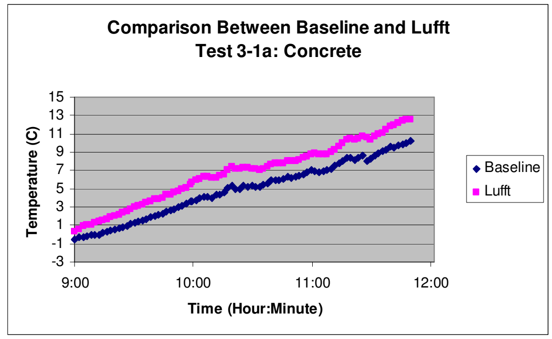
The asphalt sensors followed their respective baselines, reporting temperature increases from 1.0 to 14.0° C over the test period. The Aanderaa, Boschung, Lufft and SSI reported mean absolute errors less than 0.6° C. The Vaisala reported data every 30 minutes and had a mean absolute error of 1.5° C.

The concrete sensors followed the increasing trend of their respective baselines. However, they consistently reported temperatures approximately 2.0° C greater than their baselines. The concrete baselines began the test reporting 0.0° C while the concrete sensors generally reported initial readings of 0.5° C. After the first hour of testing, the subject sensors were reporting temperatures approximately 2.0° C greater than their baselines. At the conclusion of the test, the baselines were reporting approximately 10.0° C while the subject sensors were reporting approximately 12.0° C. See figure below.

The sun is a powerful heat source and it warms the pavement sensor from the top surface to the bottom. Thus it has a greater impact on the top of the sensor than the bottom or sides of the sensor. As the sun shines, it heats the top surface and the heat propagates through the pavement sensor. One major factor that affects when the sensor reports a temperature change depends on where the temperature sensing element is located within the sensor. The sensor material composition could also have a similar effect. Due to these and other unknown factors, the effect of solar radiation on sensor performance is difficult to understand, and more study is needed.

Below are sample graphs of the asphalt and concrete tests. Notice the concrete subject sensor reported temperatures approximately 2.0° C higher than its baseline.





Test 3-1b: Without Direct Solar Impact

This test was conducted on a cloudy morning between 9:00 and 11:50 a.m. The average wind speed was 6.8 miles per hour, and the ambient air temperature increased from -5.1° to -2.8° C during the test period.

There was no Aanderaa data during this test due to a data collection computer malfunction. The Vaisala sensor reported data in 30-minute increments.

Both the baseline and subject sensors reported initial pavement temperatures of approximately 2.0° C. For both the asphalt and concrete tests, the subject sensor data followed the same basic trend as the baseline sensors.

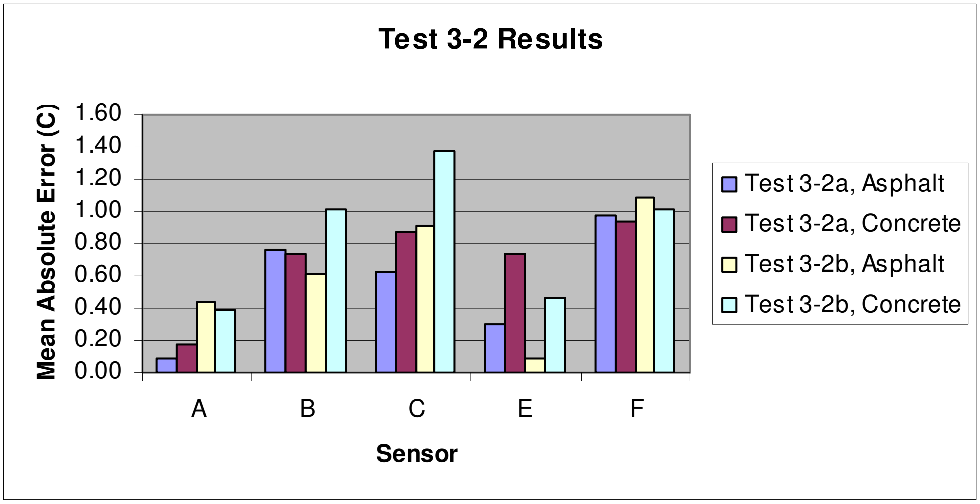
During the asphalt test, the baseline and subject sensors reported pavement temperatures increasing to 7.0° C. All subject sensors reported mean absolute errors less than 1.0° C. The Boschung, Lufft and SSI reported mean absolute errors of 0.5° C or less.

During the concrete test, the subject sensors reported temperatures increasing at a faster rate than their baselines. This was the same trend noticed during the direct solar test (3-1a). It should be noted that the subject sensor over-reporting was less pronounced during Test 3-1b and Test 3-1a.

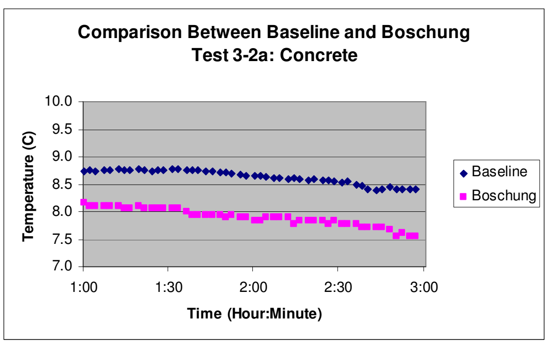
The baselines reported a final temperature around 5.0° C while the subject sensors reported final temperatures close to 7.0° C. The Boschung and SSI reported mean absolute errors less than 1.0° C while the Lufft and Vaisala reported mean absolute errors less than 1.4° C.

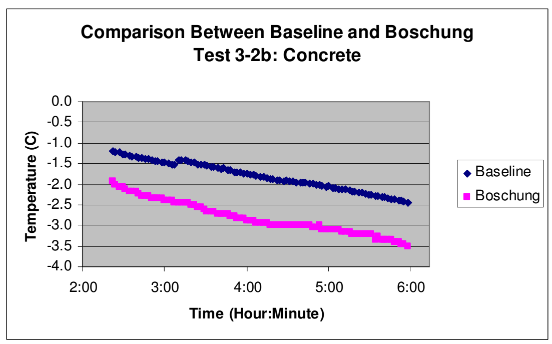
4.4.2 Field – Cold Night With and Without Strong Radiational Cooling

As was expected, the pavement temperatures dropped at a greater rate during the clear night (with radiational cooling) than on the cloudy night (without radiational) cooling. An interesting observation was that most of the subject sensors (both asphalt and concrete) reported pavement temperatures 0.5 to 1.0° C lower than their baseline sensors.



The graphs below show scenarios with and without radiational cooling. Notice that the subject sensor reported values approximately 0.7° C lower than its baseline on both tests.





Test 3-2a: Without Strong Radiational Cooling

This test was conducted on a cloudy night between 1:00 and 3:00 a.m. The average wind speed was 13.2 miles per hour, and the ambient air temperature decreased from 6.7° to 5.1° C during the test period. A cold front was approaching from the northwest.

The initial baseline temperatures varied between 8.7° and 9.0° C. At the conclusion of the test, the baseline temperatures varied between 8.4° and 8.7° C.

Overall the subject sensors followed the gradually declining trend of the baseline sensors. The Aanderaa performed the most accurately with mean absolute errors less than 0.2° C on the concrete and asphalt portions of the test. The Boschung, Lufft, SSI and Vaisala sensors consistently reported values 0.5° to 1.0° C less than their respective baseline sensors. All sensors reported absolute errors less than 1.0° C.

Test 3-2b: With Strong Radiational Cooling

On nights which have no cloud cover to radiate heat back to the earth's surface, the pavement sensor cools much more quickly from the top surface than when there is cloud cover. Even small amounts of transitory clouds can have a great warming effect on surface temperature. In clear conditions, while the bottom of the sensor remains warmer from the relatively warmer pavement beneath it, the top surface is exposed to colder temperatures. The temperature sensing element's position within the sensor and the material composition of the sensor can affect how fast these temperature sensors cool.

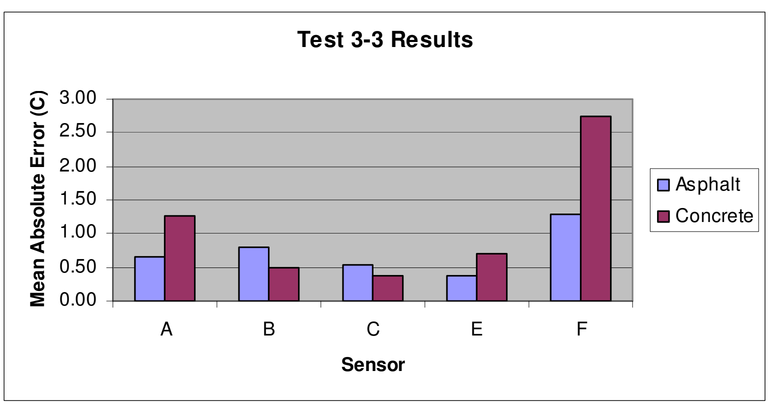
This test was conducted on a clear night between 2:00 and 6:00 a.m. The average wind speed was 2.3 miles per hour, and the ambient air temperature decreased from 0.2 to -2.2° C during the test period.

The initial asphalt temperatures varied between -0.5° and -0.7° C while the initial concrete temperatures varied between -1.0° and -1.5° C. At the conclusion of the test, both pavements reported a reading of -2.5° C.

While subject sensors followed the declining trend of the baseline sensors, they also tended to report temperatures 0.5° to 1.0° C lower than their baselines. The Aanderaa and SSI reported mean absolute error less than 0.5° C on both the concrete and asphalt tests. The remaining sensors reported mean absolute errors less than 1.4° C.

4.4.3 Test 3-3: Field: Warm Pavement With Snowfall

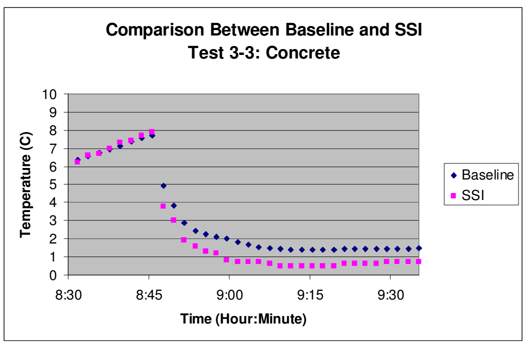
This test began at 8:37 a.m. when the ambient temperature was approximately 4.0° C and the average wind speed was six miles per hour. The concrete temperature was between 6.0° and 7.0° C and the asphalt was between 7.0° and 8.0° C. Since real snow could not be obtained, 600 pounds of crushed ice (particles ranging between dust and pea sizes) was distributed around the pavement sensors. The ice was distributed to a depth of 1.5 inches and was spread on and around the sensor so that it covered the surrounding 12 to 18 inches of pavement.

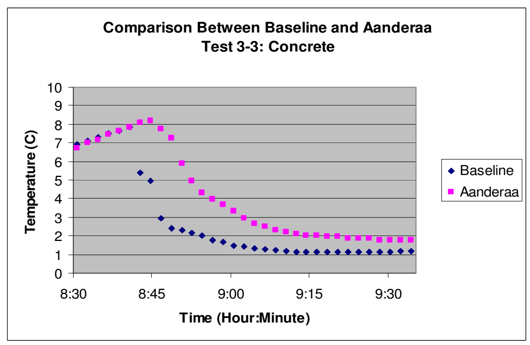


Prior to the test, the pavement temperatures were increasing due to the morning sunshine. Within five minutes of the crushed ice application, the baseline readings rapidly dropped and then stabilized between 1.0° and 2.0° C until the ice melted.

All the sensors (Vaisala excluded due to its 30-minute time increments) responded to the temperature within 10 minutes of the ice being applied. The Boschung, Lufft and SSI sensors followed the baseline temperature drop within and reported mean absolute errors of 0.8° C or less. The Aanderaa's temperature drop was approximately 5 to 10 minutes behind its baseline sensor. The Aanderaa's mean absolute errors were 0.65 and 1.27° C for the asphalt and concrete tests respectively. Only three data points were reported for the Vaisala, but its mean absolute errors were 1.28° and 0.74° C for the asphalt and concrete tests respectively.

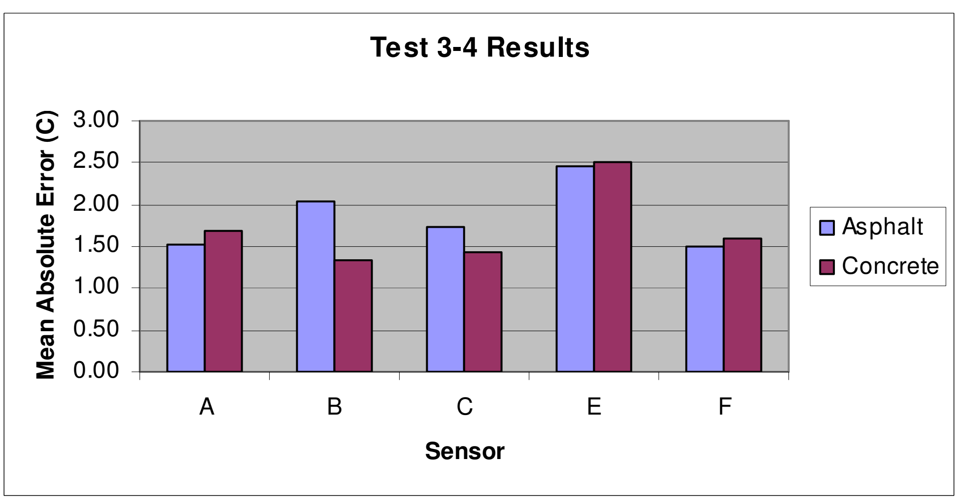
Shown below is a typical raw data graph (in this case SSI) followed by a graph illustrating the temperature delay observed with the Aanderaa sensor.





4.4.4 Test 3-4: Field: Cold Pavement With Rainfall

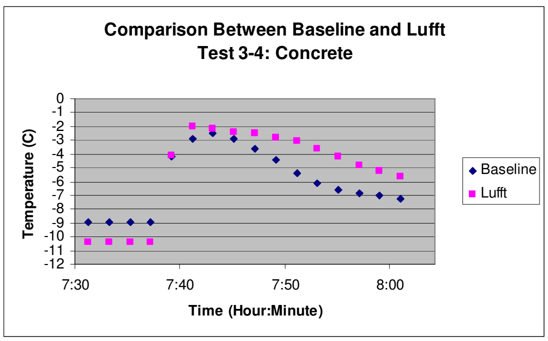
This test began at 7:35 a.m. when the ambient temperature was -12.0° C and the average wind speed was 2.4 miles per hour. The concrete and asphalt temperatures were -9.0 and -10.2° C respectively. Water was applied to the pavement using a spray bottle. Upon water application, the baseline temperatures rapidly rose to between -2.0 and -4.0° C and then gradually dropped to around -8.0° C during the following 30 minutes. See below for summarized test results.

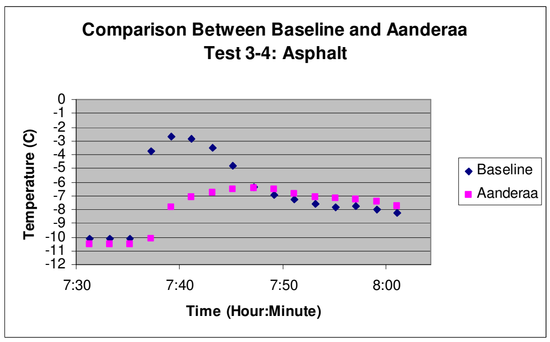


*Note: There was limited Vaisala data due to the 10-minute data intervals.

The Aanderaa, Lufft and Vaisala reported mean absolute mean errors between 1.3° and 1.7° C while the SSI reported mean absolute errors of 2.5° C. Overall, the sensor data followed the baseline trends, but there are also some discrepancies:

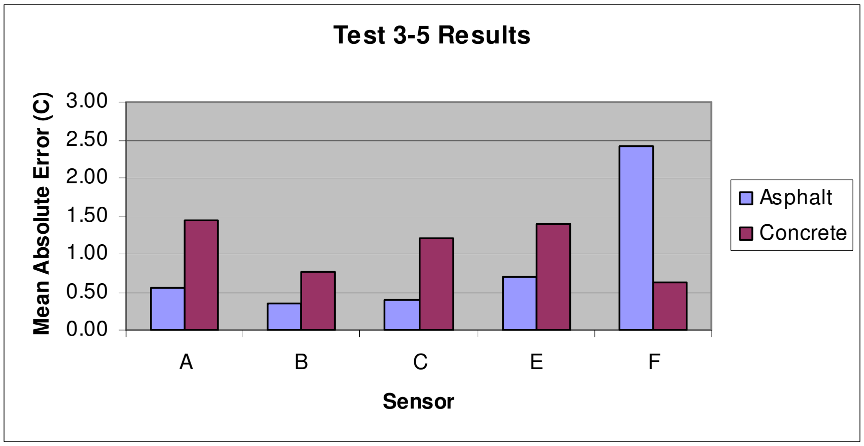
- The Lufft and SSI sensors reported temperatures several degrees higher than their baselines during the gradual temperature drop, approximately 2° and 4° C for the Lufft and SSI sensors respectively.
- The Aanderaa and Boschung didn't report as significant of a temperature increase when the water was applied as did the baseline sensors. Lastly, prior to the start of the test, the Lufft, Boschung and concrete SSI sensors all reported initial temperatures approximately 1.0 degrees lower than their baselines. A partial explanation for these discrepancies could be that the mobile Test 3-6a was conducted near the Lufft and Boschung sensors just prior to this test. Test 3-6a involved spraying the pavement with water and then parking a vehicle, equipped with the mobile sensors, over a section of the test area. Below are sample graphs of the Lufft and Aanderaa sensors.



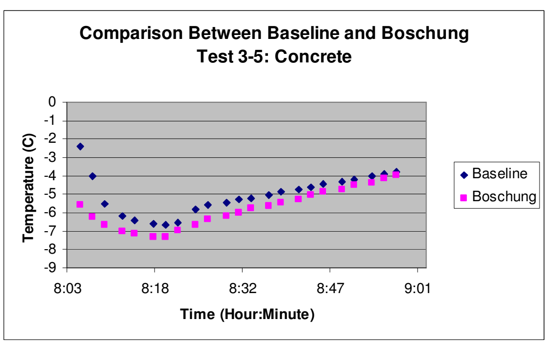


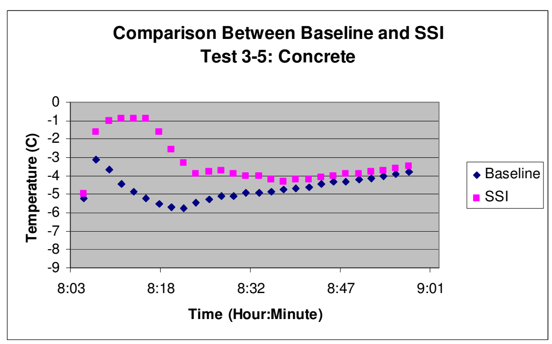
4.4.5 Test 3-5: Field – Iced Pavement With Rainfall

This test was conducted immediately after the previous test. At 8:04 a.m., water was again sprayed on the pavement sections, and the baseline temperatures jumped up several degrees from the -8.0° C initial reading. Immediately thereafter the baseline temperatures dropped. This increase and decrease occurred within a four-minute period and did not show up well on the graph. Over the next 15 minutes the temperature continued to drop, bottoming out around 8:20 a.m. between -8.0° and -6.0° C. The baseline temperatures gradually rose to -4.0° C during the next 30 minutes.



The Boschung sensor followed its baseline the most accurately, reporting absolute errors less than 0.8° C. Compared to their baselines, the concrete Aanderaa, Lufft and SSI sensors experienced a delay of approximately 15 minutes during the application of the water. On the asphalt section, the sensors showed a delay of approximately five minutes. The concrete Aanderaa, Lufft and SSI sensors reported mean absolute errors between 0.4° and 1.5° C during the test period. The Vaisala reported data every 10 minutes and had mean absolute errors of 0.6 and 2.4° C on the concrete and asphalt tests respectively. Shown below are graphs of the Boschung and Aanderaa's test data. The subject sensor's temperature delay is illustrated in the second graph.





4.4.6 Field – Mobile Sensor Field Evaluation

Throughout Test 3-6, both mobile sensors followed the trend of their baselines and reported average errors of 0.7° and 1.9° C for the Control Product and Sprague sensors, respectively.

However, during portions of each test, the Control Products sensor would over-report the baseline temperature by approximately 1.0° C. The accurate results during certain portions of the testing rules out miscalibration as the cause. Differing pavement emissivities could be the cause. However, additional field testing is required to confirm this hypothesis. Table 11 shows three types of averages for each of the mobile sensor field tests.

During some field tests (Test 3-6a and Test 3-6c), the Sprague sensor consistently under-reported the pavement temperature by approximately 2.0° C. Test 3-6a ruled out the possibility of the sensor mistakenly reporting the air temperature. The sensor's accuracy during Test 3-6b ruled out a field calibration problem. The sensor's accuracy during the dry concrete portion of Test 3-6c makes determination of the cause of error difficult. As with the Control Products sensor, perhaps differing emissivities could be the cause. Further field testing is necessary to determine the true cause of the under-reporting error.

Table 11: Mobile Sensor Field Evaluation Summary

Test 3-6a (Cold Pavement with Rainfall): Asphalt

Sensor	Mean Difference (ºC)	Mean Absolute Difference (ºC)	Root Mean Square Difference (ºC)
Sprague	-1.39	1.39	1.52
Control Products	-0.90	0.90	0.94

Test 3-6a (Cold Pavement with Rainfall): Concrete

Sensor	Mean Difference (ºC)	Mean Absolute Difference (ºC)	Root Mean Square Difference (ºC)
Sprague	-0.69	1.29	1.45
Control Products	-0.41	0.42	0.69

Test 3-6b: Ice Bath Test

Sensor	Mean Difference (ºC)	Mean Absolute Difference (ºC)	Root Mean Square Difference (ºC)
Sprague	-2.52	2.95	6.34
Control Products	0.61	1.17	3.86

Test 3-6c (Emmissivity Test): Overall Test Summary

Sensor	Mean Difference (ºC)	Mean Absolute Difference (ºC)	Root Mean Square Difference (ºC)
Sprague	1.11	1.31	1.48
Control Products	0.33	0.39	0.57

Test 3-6c (Emmissivity Test): Summary by Sub-Test (mean errors)

Sensor	Dry Concrete (ºC)	Ice Bath (ºC)	Iced Concrete (ºC)	Ice Bath (ºC)	Dry Asphalt (ºC)	Iced Asphalt (ºC)
Sprague	-1.08	0.40	-1.85	-0.42	-1.76	-1.63
Control Products	-0.15	0.86	-0.15	1.34	0.50	0.64

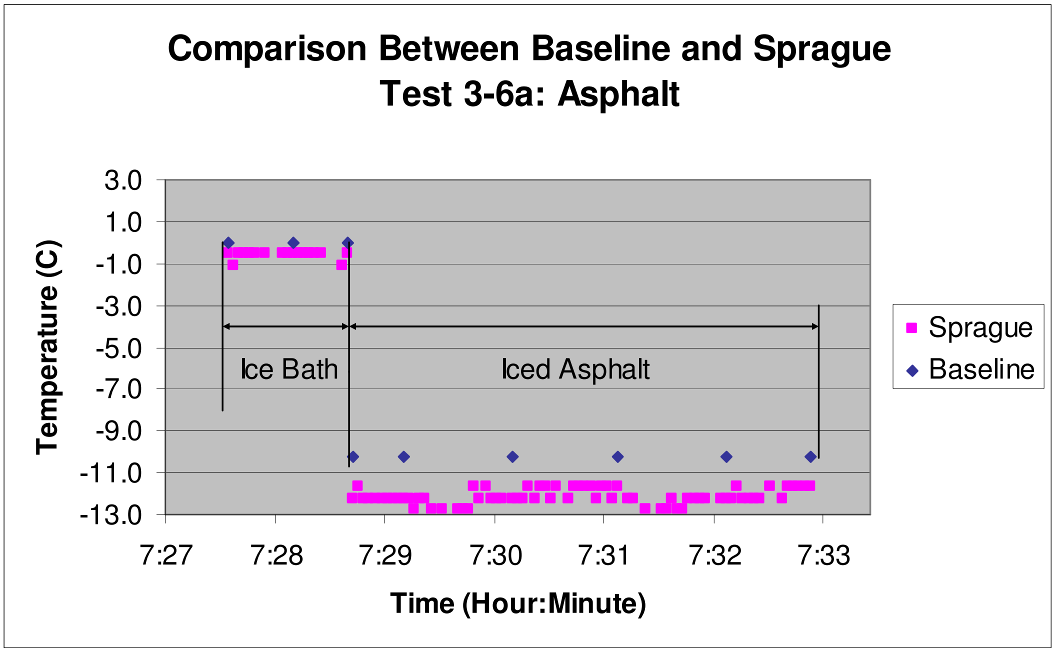
Test 3-6a: Cold Pavement With Rainfall

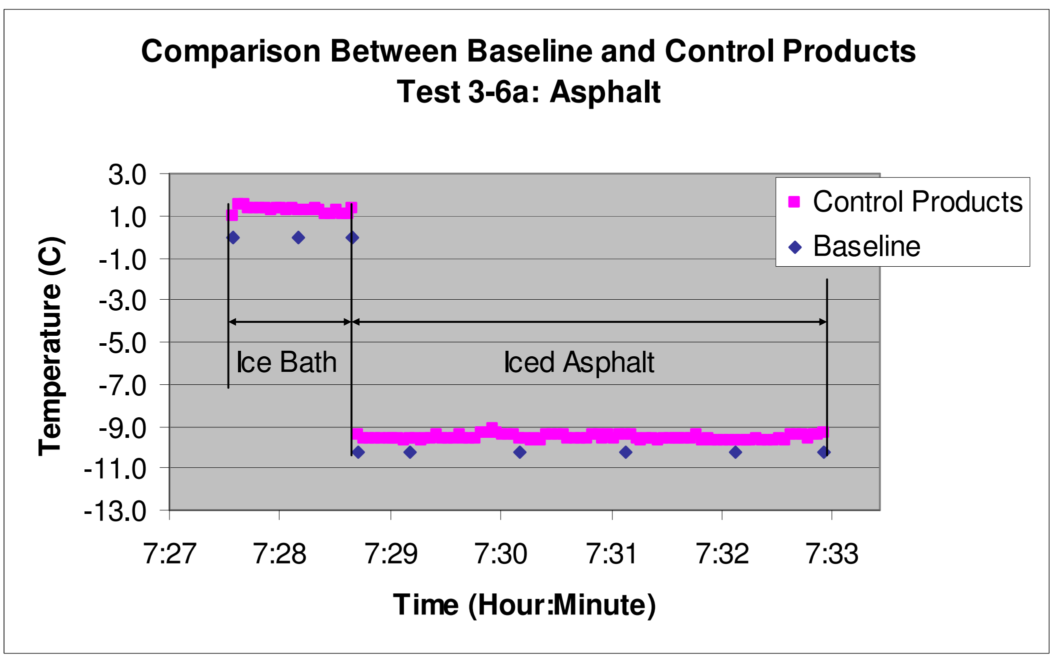
At the beginning of each test (concrete then asphalt), the mobile sensors were aimed at an ice bath for reference purposes. During the ice bath data collection period, the pavement section was sprayed with water from a spray bottle. Next, the ice bath was removed and the vehicle (and attached mobile sensors) was parked over the iced test section.

During the testing, the average wind speed was 3.2 miles per hour and the ambient air temperature was -13.0° C. The pavement temperature was constant at -8.7° and -10.3° C for the concrete and asphalt sections respectively. The baseline temperature was taken from the nearest pavement thermistor and did not measure the ice bath temperature. The ice bath was assumed to be 0.0° C.

During the ice bath test, the Control Products sensor reported constant readings of approximately 1.0° C while the Sprague reported readings within 1° C of the presumed 0.0° C ice bath.

When the mobile sensors were positioned over the iced pavement, the Control Products sensor reported temperatures within 0.2° and 1.0° C of the baseline for the concrete and asphalt pavements respectively. The Sprague reported temperatures approximately 2.0° C below its baseline for the concrete and asphalt pavements. Samples of the Control Products and Sprague data are shown in the following graphs.





Test 3-6b: Ice Bath Comparison Test

During this test, the average wind speed was 1.0 miles per hour and the ambient air temperature ranged between 2.6 and 3.2° C. Prior to the test, both sensors were mounted to the front of the test vehicle and were allowed to acclimate to the ambient temperature for 60 minutes.

Note that this location is near the vehicle's radiator which had an unknown impact on the temperature readings. It is assumed that turbulent flow from the moving vehicle would minimize any impacts, but further study would be required to prove this hypothesis.

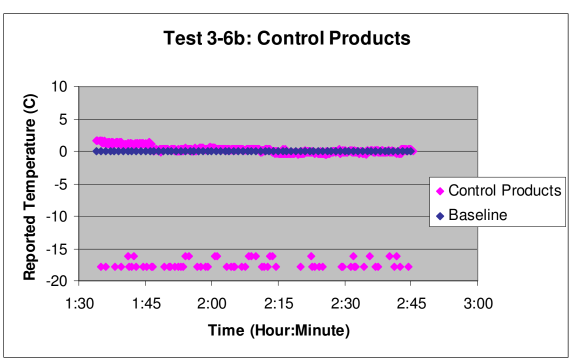
After 60 minutes, an ice bath, presumed to be 0.0° C, was mounted beneath the sensors. The sensors were then allowed to acclimate to the ice bath for 15 additional minutes. At 1:45, the vehicle was driven continuously for 60 minutes at speeds between 30 and 50 miles per hour.

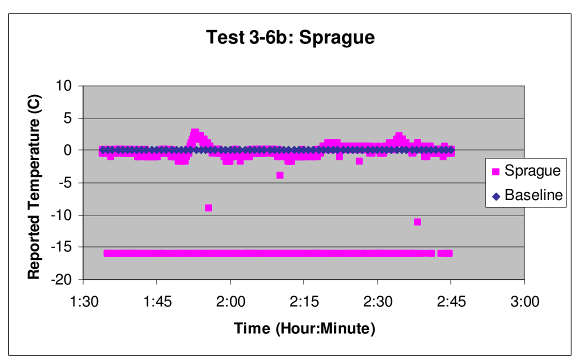
The Control Products sensor mostly reported constant readings around 1.2° C during the initial ice bath acclimation and readings close to 0.0° C during the driven portion of the test. The Sprague generally reported temperatures within 1.0° C of the baseline.

Both sensors reported a significant number of data points near -17.0° C. These -17.0° C readings correspond to approximately 0.0° F. It is possible that these readings represent intermittent power or communications errors. In other words, the sensor might output 0.0 in the event of an intermittent error. The live road conditions, such as vibrations or electrical interference, could have caused these failures.

The Control Products sensor reported a 1.0° C drop after the vehicle began traveling. This could suggest that the sensor was affected by the ambient temperature immediately above the targeted ice bath. Also, it is possible that heat which radiated from the vehicle has a lesser effect on the temperature readings as the vehicle started traveling.

Overall, the mean absolute errors were 1.2° and 3.0° C for the Control Products and Sprague sensors respectively. The mean absolute errors were calculated with the assumption that the ice bath was a constant 0.00° C. Raw data is shown in the following graphs.

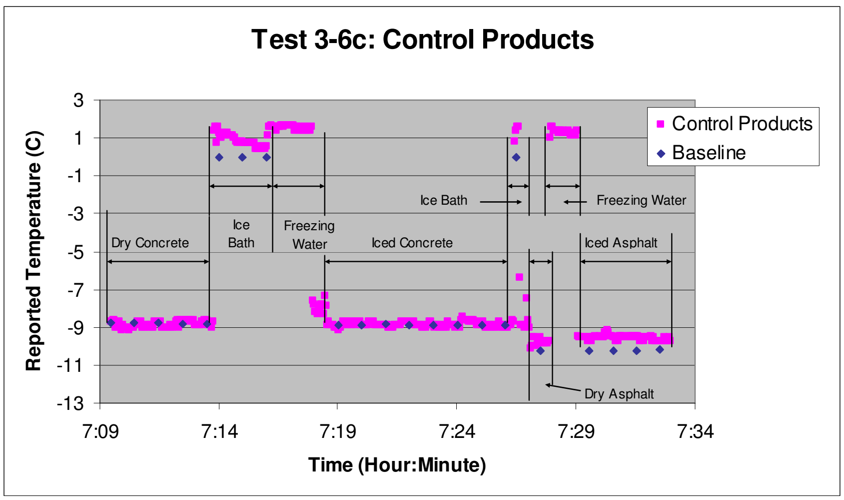


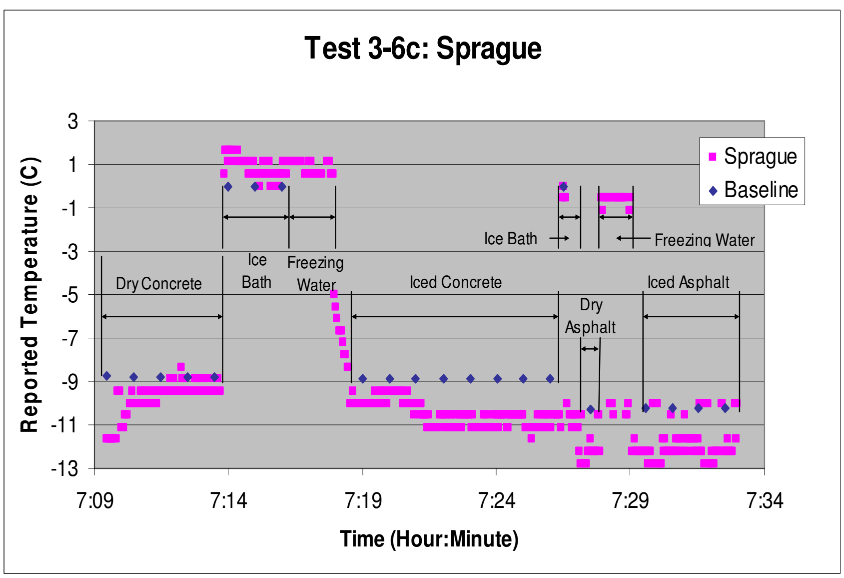


Test 3-6c: Emissivity Check

This test was conducted between 7:10 and 7:34 a.m. The average wind speed was 2.4 miles per hour, and the ambient air temperature was -13.2° C. The baseline asphalt and concrete pavement temperatures were -10.2 and -8.7 respectively throughout the test.

Prior to the test, both mobile sensors were acclimated to the ambient environment for at least 30 minutes. At 7:10, the sensor vehicle was parked over the dry concrete test-section of roadway. At 7:14, an ice bath (presumed to be 0.0° C) was placed under the sensors. At 7:17, the ice bath was removed, and water was then sprayed onto the concrete pavement section; by 7:19 the water had frozen. At 7:27, an ice bath was again briefly positioned (for approximately 30 seconds) underneath the mobile sensors. At 7:27:30 the vehicle moved and parked over the dry asphalt test section. At 7:28:30, the pavement was sprayed with water; by 7:29:30 the water had frozen. The raw data graphs for each sensor are shown below.





The Control Products data clearly reflected the described test procedures, reporting a mean absolute error of 0.4° C using the shown baseline data points. The Sprague sensor data, with its 0.55° C data resolution, illustrated the described test procedure significantly less clearly than the Control Products sensor. The data resolution makes it hard to differentiate between test steps and hard to compare small temperature differences. The mean absolute error for the Sprague was 1.3° C using the shown baseline data points. Table 12 summarizes the test results by sub-test.

Table 12: Test 3-6c Summary by Sub-Test (mean errors in °C)

Sensor	Dry Concrete	Iced Concrete	Dry Asphalt	Iced Asphalt
Control Products	-0.15	-0.15	0.50	0.64
Sprague	-1.08	-1.85	-1.76	-1.63

The Control Products sensor reported temperatures nearly identical between the dry and iced pavement sub-tests (less than 0.2° C differences on each pavement type). The Sprague sensor also reported the dry and iced asphalt to be nearly identical (less than a 0.15° C difference). During the concrete test, however, the Sprague reported the temperature of the dry concrete to be 0.7° C higher than the iced concrete. These results suggest that the emissivity of the dry pavement is similar to the emissivity of the iced pavement. This tendency is consistent with the findings of a similar test performed by Ron Tabler [5].

However, it should be noted that the averaged mean absolute errors for the ice bath portions of this test were 0.8° C. Additionally, the Sprague sensor reported relatively large errors varying between 0.4 and 1.9° C throughout the sub-tests. These findings suggest that further testing is necessary for make formal conclusions regarding the effects of emissivity on mobile sensor accuracy.

5 Conclusions and Suggested Research

Through a wide range of Aurora-approved laboratory and field test procedures, this study met its objective of evaluating the surface temperature reporting performance of various models of both in-pavement and mobile pavement temperature sensors in varying environmental conditions.

The following conclusions were drawn from the laboratory and field test results presented within the main body of this report. It is not the intent of this report to draw subjective conclusions regarding the performance of individual sensors or to recommend which units performed the best. It is left to the readers to examine the results and determine which sensor might best meet their needs. Thus, the conclusions below are general in nature.

All Sensors

- Throughout the variety of environmental conditions tested, on average, the sensors reported surface temperatures within 0.8° C (1.4° F) of the actual pavement surface temperature.
- The application of sodium chloride to the sensors had an insignificant impact on sensor temperature reporting performance.
- Solar impact was difficult to reproduce in the laboratory environment because non-uniform spatial distribution of the simulated solar light caused different surfaces and locations of the pavement to heat differently.

In-Pavement Sensors

- In general, most in-pavement sensors tended to read within 1.5° C (2.7° F) of their baseline sensors.
- Laboratory tests indicate that the performance of in-pavement sensors was not significantly affected by pavement type.
- Field tests, however, indicated that in-pavement sensors installed in asphalt pavement reported more accurate surface temperature readings than in-pavement sensors installed in concrete pavement. This was confirmed by a statistical significance test.
- Field temperature tests indicate that in the "real world," the in-pavement sensors might not track ambient temperature fluctuations as well as in the laboratory. The differences are most pronounced when solar radiation is present, suggesting that the connection between solar radiation and sensor performance is complex. This may be due to the effects of temperature cycles (solar heating and radiational cooling) or the pavement's thermal properties. Additional field testing is recommended to quantify these factors.
- Sensors with temperature sensing elements beneath the surface of the pavement are less responsive to rapid temperature fluctuation.

Mobile Sensors

- In the laboratory and field, pavement type was shown to have a noticeable effect on mobile pavement sensor performance. The mobile sensors, on average, performed 0.5° C (0.9° F) more accurately on the concrete tests.

- Mobile sensor mounting height did not have a significant effect on accuracy.

Suggested Research

The laboratory and field tests conducted for this project revealed a great deal of information on the performance of RWIS sensors under a variety of conditions. Analysis of the test results also reveals areas where additional research would be beneficial to the RWIS community. The following items are proposed as opportunities for further research:

- The current research focused exclusively on temperature. Other parameters, such as freezing point and surface state, could be evaluated with the equipment currently available. A follow-up study to analyze these parameters would be a cost-effective way of assessing the parameters by using the test sections and sensors already procured.

- The field data revealed some interesting effects related to radiational cooling and solar heating that could not be replicated in the laboratory. Further research into these effects would help further the understanding of RWIS sensors.

- Additional field investigation of the mobile sensors would reveal how varying pavement type and environmental conditions, such as snow, ice, wind or solar radiation, affect sensor performance.

The study results offer detailed understanding of the range of accuracy that can be expected with pavement temperature sensors. Development of an *acceptable* range of accuracy could be developed with the data obtained in this study. This step is left to the reader to determine because each agency has its own needs, which may vary depending on the application. In general, the sensors were found to perform without significant failures and within a definable range. The greater RWIS community may want to explore the creation of an acceptable range of accuracy, possibly through other RWIS projects like the Clarus initiative.

6 References

1. Devore, Jay, *Statistics: The Exploration and Analysis of Data*, 2nd Edition, Duxbury Press, 1993.

2. Minnesota Department of Transportation, *Standard Specifications for Construction*, 2000 Edition.

3. *Road Weather Information Systems, Volume 2: Implementation Guide*, Strategic Highway Research Program (SHRP-H-351), 1993.

4. Ohio University, *Evaluation of ODOT Roadway/Weather Sensor Systems of Snow and Ice Removal* (FHWA/OH-2003/008C), 2003.

5. Tabler, R. D., *Comparison of RoadWatch and Control Products, Inc., Model 999J Infrared Sensors*.

Appendix A

Literature Summary

Appendix A
Literature Summary

No.	Name and Contact	Literature Source and Study Description
1	Doug Jonas Matrix Management Group matrixdlj@aol.com	Group discussion about IR/Pavement sensor comparative accuracy. http://www.sicop.net/IR-Pavment%20Sensor%20Comp,%202-26-00.pdf
2	Duane Smith Iowa State University 515-294-8817 desmith@iastate.edu	"Concept Highway Maintenance Vehicle Final Report: Phase II", Center for Transportation Research and Education (CTRE) at Iowa State University, December 1998 http://www.ctre.iastate.edu/Research/conceptv/conveph2/ Chapter 9 includes information regarding using temperature sensors on winter maintenance vehicle to automatically collect air and pavement temperature data. Appendix H is a referenced report that provides results of a comparative performance test conducted with Control Products 996A and a Sprague RoadwayWatch surface temperature monitoring system. The test was performed by Braun Intec Corporation, Portland, Organ
3	Roger Green Office of Pavement Engineering Ohio DOT Office Phone: 614-995-5993 http://www.dot.state.oh.us/pavement/ Dr. Shad Sargand Ohio University 740-593-1467 ssargand@bobcat.ent.ohiou.edu	OHIO/DOT Strategic Highway Research Program (SHRP) Test Road Project http://www.dot.state.oh.us/pavement/Research/del23.htm As part of the support for the Strategic Highway Research Program (SHRP), the Ohio Department of Transportation, in conjunction with the Federal Highway Administration, constructed a comprehensive test road encompassing four of nine experiments in the Specific Pavement Studies (SPS). This project affords SHRP with a unique opportunity to compare the performance of pavement sections in these experiments at one site where topography, soil, and climate are uniform.
4	Graves Clark Kentucky Transportation Center University of Kentucky 606-257-4513, Ext. 248 cgraves@engr.uky.edu	"Evaluation of Road Weather Information System", Research Report, May 1999. The report describes the study that monitored and evaluated the Kentucky Transportation Cabinet's Road Weather Information System. Pavement sensors and surface temperature were discussed in the report,

No.	Name and Contact	Literature Source and Study Description
5	F. Fabre, A. Klose Commission of the European Community	Cost 309 Road Weather Conditions Report. EUR 13847 EN, 1992. The report includes the information about the Test of Roadway Weather Monitoring System and Sensors. Members and Experts in project management committee are listed in the report.
6	Lars Frimodig Swedish National Road Administration 46-243-750-00 Dr. Torbjorn Gustavsson Bergaba Consultants 46-31-84-83-80	Cost 309 Test of Road Weather Monitoring System and Sensors
7	Marilyn H Burtwell Transportation Research Laboratory UK 44-01344-770214 marilynb@h.trl.co.uk	"Assessment of Road Surface Freezing Point Sensors for the UK", Marilyn Burtwell, Transport Research Laboratory. Pages 767 to 778. Preprint for the 1998 Xth PIARC International Winter Road Congress in Lulea, Sweden. This paper describes a series of road experiments to monitor the performance of all types of sensors, including roadway and laboratory tests.
8	Dan Roosevelt Virginia DOT 804-293-1924 dsr2n@virginia.edu	"Standardized Testing Methodologies for Pavement Sensors", Castle Rock Consultants, December 7, 1999 The project researched procedures for calibrating and testing RWIS pavement sensors. Contact List for the project is included in the Appendix E.
9	Edward Boselly Matrix Management Group	"An Analysis of the PM-4 Non-contact Thermometer and Performance Characteristics of the SCAN Surface Sensor", Surface Systems, Inc. April 11, 1991 The study documented the performance test of the PM-4 SCAN thermometers.

No.	Name and Contact	Literature Source and Study Description
10	ODOT Research Project Ohio University - Helmut Zwahlen Abner Johnson - ODOT	"Evaluation of ODOT Roadway/Weather Sensor Systems for Snow and Ice Removal Operations" http://www.dot.state.oh.us/divplan/research/research_sp&r/pdfs/AppB147580.pdf This test focused on Road Weather Information System (RWIS) pavement sensors, which were tested under controlled conditions in a climate chamber. Testing included temperature, chemical concentration and liquid depth measurement. The testing was done in the summer of 2002. The final report has not been published.
11	Ministère de l'Equipment des Transports et du Logement (METL) France	"Homologation Specifications for Road Stations in Winter-Maintenance Decision Support Systems" This report was written in French and was translated into English. We have the first fifty-three pages of this report. This report defines methodologies and procedures.
12	Scharching, Helmut	"Results of a Field Testing of Six Different Ice Warning Systems", Proceedings of the International Workshop on Winter Road Management, January 26-29, 1993 Sapporo, Japan. Pages 185 – 199

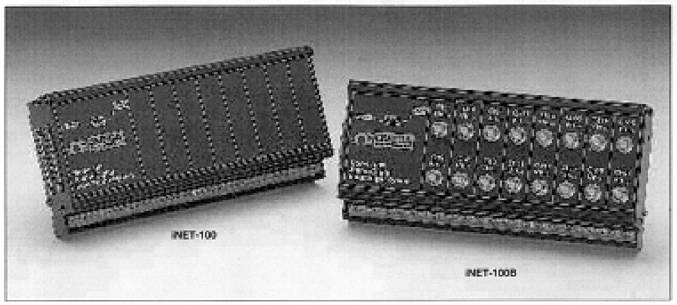
Appendix B

Baseline Sensor Specifications

NEW™

instruNet Series Direct Sensor to Data Acquisition

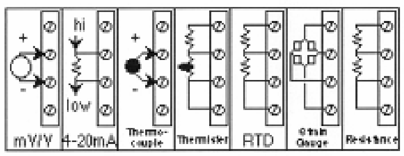
YEAR 2000 COMPLIANT



1 YEAR WARRANTY — MADE IN USA

OMEGA CARE Extended Warranty Program

$1480
Basic System With Software



- **High Accuracy Data Acquisition for Windows 95/NT & Macintosh Computers**
- **16 Single-Ended/ 8 Differential 14 Bit Analog Inputs, 8 Analog Outputs and 8 Digital I/O**
- **Controller Card Includes 10 Counter/Timer Channels**
- **Direct Connect to RTD, Thermocouple, Voltage, Thermistor, Bridge and Strain Gage Sensors**
- **166 Ks/sec Throughput to RAM or Disk**
- **Each Channel has Independently Programmable Analog Filters, Integration Time, Voltage Range and Sample Rate**
- **Programmable Digital Filters on All Channels**
- **Includes Strip/Chart Software and Drivers for C, Visual Basic, HPVEE, and TestPoint**

Optional LabVIEW Drivers are available.

instruNet provides ten's of microvolts of absolute accuracy instead of ten's of millivolts, at the same cost and at the same throughput rates as typical general purpose data acquisition boards. It does this with a completely different topology where the analog electronics are close to the sensor in electrically quiet boxes outside your PC, and noisy digital electronics are left inside the computer. The external boxes contain signal conditioning amplifiers for each channel and can directly attach to sensors such as thermocouples, thermistors, RTD's, strain gages, resistance sources, current sources and voltage sources. The box returns engineering units to your PC (e.g. °C, Volts, Amps).

At the heart of the real-time system is a PCI or PC-card controller board that plugs into a Windows 95/NTx86 or Macintosh computer. Each controller contains a 32 bit microprocessor with 256KB of RAM that manages the external "network" of devices. All real-time tasks are off-loaded to this processor, therefore the host computer is not burdened with real-time issues. Each instruNet INET-100 box provides, 16 single-ended/8 differential analog inputs, 8 analog outputs and 8 digital I/O lines. The INET-100 includes 44 screw terminals. The INET-100B version adds 16 BNCs for analog inputs. The controller's themselves provide 10 counter/timer channels each of which can function as a digital input bit, a digital output bit, a clock output channel or a period measurement input channel.

C-17

Distributed and Expandable

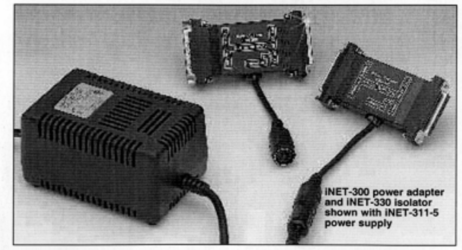
The instruNet system is ideally suited for distributed measurement and control systems. The network cable can extend up to 1000 feet. Each controller card in the PC can connect to up to 16 instruNet boxes for a total number of 256 analog inputs, 128 analog outputs and 128 digital I/O. For additional inputs, multiple controller cards can be placed in one computer with the maximum number of controller cards limited only by the number of available slots in the computer.
Since each controller card has its own microprocessor, multiple cards do not place any additional burden on the computer. It should be noted that multiple instruNet boxes on a single network may degrade the maximum system throughput of 166Ks/sec.

Performance

The instruNet system supports the digitizing of multiple channels at a maximum aggregate sample rate of 166Ks/sec, where each channel can be digitized at it's own rate. This maximum rate decreases when: the total cable length increases, optical isolation is used, digital filtering or plotting is enabled, more boxes are added, more channels are digitized, amplifier gain is increased, or spooling to disk is added. Each channel can be independently digitally filtered with low-pass, high-pass, band-stop and band-pass filters; where the filter specification for each channel is independently set in software.
Each channel provides a programmable analog low pass filter with programmable A/D measurement integration time. The network can be hundreds of feet long and can support multiple hardware devices connected together in a daisy-chain configuration. The start of digitizing can be triggered from any channel. There are no jumpers or pots; the system automatically self-calibrates on power-up. Since instruNet is modular, it can easily be expanded as needs evolve. One can easily move the system hardware from one computer family to another, since the various controllers are functionally identical.

High Current Version (HC)

The INET-100HC is similar to the INET-100, yet the voltage output channels have a higher drive capability, providing up to 15mA of current to capacitive loads as high as 0.01uF. The INET-100 and INET-100B devices support only 4mA/.001uF voltage output drive. The INET-100HC is recommended for use with sensors that require excitation, such as strain gages, RTDs and thermistors since these sensors may exceed the current or capacitive drive limits of the INET-100 or INET-100B. The INET-100HC provides greater compatibility with sensors that have capacitive loading on the excitation lines, therefore, the HC version is recommended for all sensors requiring excitation including RTDs and thermistors. Since the HC version has a greater power demand, an external power supply must be used. The INET-311-2, should be used for one INET-100HC and INET-311-5 can be used to power up to three INET-100HC boxes.



iNET-300 power adapter and iNET-330 isolator shown with iNET-311-5 power supply

Software

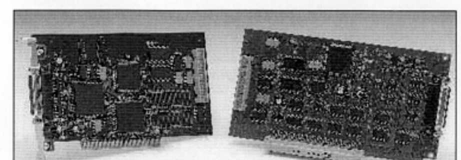
"instruNet World", is a FREE application program. It manages, monitors and operates the instruNet system. It digitizes long continuous waveforms, spools them to disk, views incoming waveforms in real-time and then allows post acquisition viewing-much like an oscilloscope or strip chart recorder.
instruNet World provides a spreadsheet-like environment where one can set and view channel parameters such as sensor type, integration time, analog filter, and digital filter. Each channel has it's own row in the spreadsheet, with the various options in the columns.
instruNet is also compatible with a variety of off-the-shelf software products including TEST Point, HPVEE, SuperScope II Macintosh; Microsoft Excel 8 for Windows, DasyLab and Labtech Notebook (consult the factory for the availability of DasyLab and Labtech drivers).
For users writing their own programs, instruNet includes drivers callable from any 32 bit C compiler, and Visual Basic (v4.0 or greater). The driver includes a main routine, called "iNet( )", that reads or writes any of the options or channels on the system. Optional drivers are also available for LabVIEW software.

instruNet BASIC

The iNet-350 accessory adds optional software support for instruNET BASIC. This software enables users to automate the setting up of channels, digitizing, viewing results, and saving to disk.
It is predicated on the BASIC programming language and features many additional commands that facilitate working with instruNet hardware. instruNet BASIC builds on the instruNet World strip chart recorder by automating common tasks done at experiment time.

Power Requirements

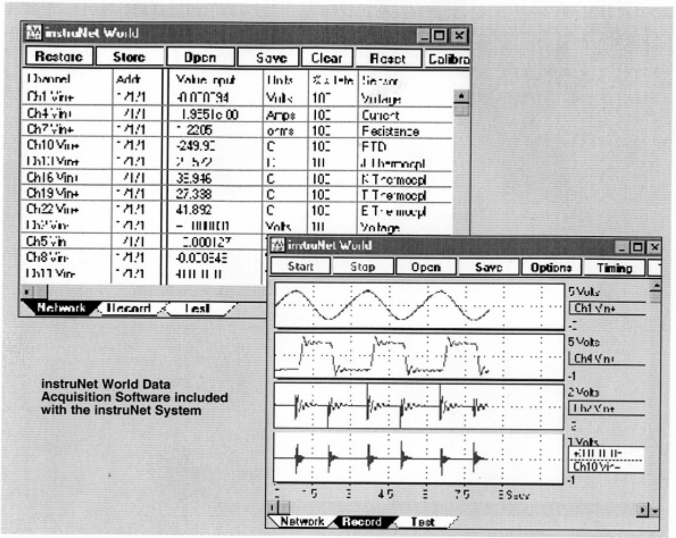
Since instruNet is powered directly from the iNET-200/2200 controller card, it is possible to exceed the power capacity of the controller card if multiple instruNet iNET-100 boxes are attached to a network. For systems with more than 3 (1 in the case of the PC-card controller) instruNet boxes on a network, external power is required. Two power adapters are available, the iNET-300 power adapter and the iNET-330 adapter/isolator. Both devices connect in line with the instruNet communications cable, the iNET-300 provides power only, the iNET-330 provides power and electrical isolation between the iNET-100 boxes and the computer. Isolation is useful in eliminating ground loop problems. Both the iNET-300 and iNET-330 require either the iNET-311-2 or iNET-311-5 power supply. The INET-311-2 can power three INET-100/100B or one INET-100HC. The INET-311-5 can power 5 INET-100/100B or three INET-100HC. The iNET-230 controller card does not provide power, the iNET-311 or iNET-312 power supply must be used with this card



PCI and Nubus Controller Cards

C-18

C



instruNet World Data Acquisition Software included with the instruNet System

Voltage Range/Accuracy

Voltage Range	Integration (Seconds)	Accuracy
±5 V	1 ms none	±700μV ±1500μV
±0.6 V	1 ms none	±75μV ±150μV
±80 mV*	1 ms none	±15μV ±45μV
±10 mV*	1 ms none	±10μV ±30μV

*±80 mV and ±10 mV are nominal ranges, the actual ranges may be as low as ±78 mvV and ±8 mV respectively

Thermocouple Ranges/Accuracy

Thermocouple	Range	Accuracy
J	-210 to -100°C -100 to 1200°C	±0.8°C ±0.5°C
K	-200 to -50°C -50 to 1360°C	±0.8°C ±0.6°C
T	-200 to -100°C -100 to 400°C	±0.8°C ±0.5°C
E	-200 to -60°C -60 to 1000°C	±0.7°C ±0.5°C
R	-50 to 70°C 70 to 1768°C	±3.5°C ±2.0°C
S	-50 to 150°C 150 to 1768°C	±2.8°C ±1.8°C
B	250 to 600°C 600 to 1300°C	±3.8°C ±2.0°C
N	-200 to -110°C -110 to 1260°C	±1.3°C ±0.8°C

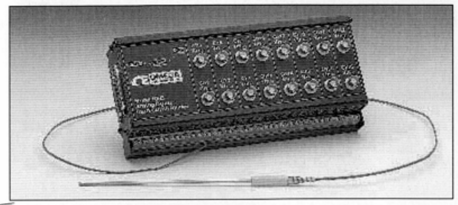
Accuracy includes cold junction compensation, voltage measurement and linearization errors.

RTD Accuracy Ranges

RTDs with $\alpha = 0.00385$ and 0.00392 supported. One user supplied shunt resistor per RTD channel is required.

RTD	Range	Shunt	Accuracy
100Ω	0 to 200°C	1KΩ	±0.37°C
100Ω	0 to 850°C	2KΩ	±1.0°C
500Ω	0 to 200°C	4.7KΩ	±0.38°C
500Ω	0 to 850°C	10KΩ	±0.9°C
1000Ω	0 to 200°C	10KΩ	±0.36°C
1000Ω	0 to 850°C	20KΩ	±0.85°C

C-19



Qty

To Order *(Specify Model No.)*

Qty	Model No.	Price	Description
	iNET-100	$890	instruNet external A/D box with screw terminal connections
	iNET-100B	990	instruNet external A/D box with screw terminal and BNC connections
3	iNET-100HC	990	Same as INET-100 with 15 mA excitation current.
1	iNET-200	590	PCI -Bus controller card for Windows 95/NT or Macintosh computers (controls up to 16 iNET-100's)
	iNET-220	590	Nubus controller card for Macintosh computers (controls up to 16 iNET-100's)
	iNET-230†	590	PC-Card controller, type II (requires iNET-311 or iNET-312)

The iNET-2xx controllers include a complete user's manual, instruNet World data acquisition software, driver software and network terminator.

The iNET-100/100B includes a 10 ft. cable for connecting the iNET-100/100B to the controller card or other iNET-100/100Bs.

***Ordering Example: iNET-100** external A/D box and **iNET-200** controller card, $890 + 590 = **$1480**.*

†Consult Engineering for availability of WIN/NT support for iNET-230.

Accessories

Qty	Model No.	Price	Description
1	iNET-300	$60	Power adapter, required if using more than 3 iNET-100 boxes with the PCI and NuBus controller card or if using more than 1 iNET-100 box with the PC card controller (no signal isolation, requires iNET-311 or iNET-312 power supply)
	iNET-330	290	Optical isolator, isolates signal and power lines (replaces iNET-300, requires iNET-311 power supply)
	iNET-311-2	60	Power supply, 110V to 5V/0.8A & ±12V/0.24A, used with iNET-300/ 330/230 (powers 3 iNET-100/100B or 1 iNET-100HC)
	iNET-311-5	130	Power supply, 110V to 5V/2A & ±12V/0.5A, used with iNET-300/330/230 (Powers 5 iNET-100/100B or 2 iNET-100HC boxes)
	iNET-322-5	130	Power supply, 220V to 5V/2A & ±12V/0.5A, used with INET-300/330/230 (Powers 5 iNET-100/100B or 2 iNET-100HC boxes)
	iNET-340	50	DIN rail mounting brackets for one iNET-100
	iNet-34S	75	34 pin screw terminal panel, breaks out digital I/O on iNET-2xx controller (requires iNET-34W3F cable)
	iNET-34W3F	25	3 ft 34 wire ribbon cable to connect iNET-34S to iNET-2xx controller card
	iNET-350	390	instruNet BASIC software option, includes disk, manual and software license
	iNET-380	195	LabVIEW drivers for Mac and Windows 95
	OMX-R(*)	10	Precision shunt resistor, insert resistance code.

****Note:** Insert resistance code in Ohms.*
Available resistance codes are 200, 1K, 2K, 4.7K, 10K, 20K and 47K.

Ordering Example: OMX-R2K** is a 2K* precision shunt resistor,**$10.

C-20

NEW

C

Specifications

Analog Inputs Number: 16 single-ended/8 differential
Resolution: 14 bit
System Throughput: 166K samples/sec
Signal To Noise Ratio: 78 dB
Linearity: Differential ±1.5 LSB; Integral ±2 LSB
Input Overvoltage Protection: ±15V
Input Impedance: >22MΩ, 3pf
Common Mode Voltage: ±5V min (CMR ±80 dB)
Gain and Offset Drift: ±5 ppm/°C of 5V FSR; offset self caled to 0

Thermistor Accuracy/Ranges

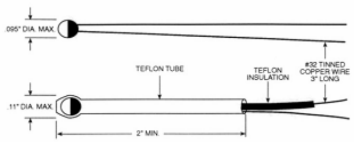
All OMEGA 44xxx series thermistors supported. (Contact factory for other thermistors.) One user supplied shunt resistor per thermistor channel is required.

Range	Shunt	Accuracy
-80 to 40°C	47KΩ	±0.2°C
0 to 70°C	4.7KΩ	±0.1°C
0 to 200°C	200Ω	±0.4°C
-40 to +70°C	4.7K	±0.15°C

Analog Outputs Number: 8
Resolution: 8 bit
Output Range: ±5V @ 5 mA for iNET-100/100B, 15 mA for iNET100HC
Output Protection: Short-to-ground continuous
Output Settling Time: 4μs (to ±½ LSB, ±5 V step)
Analog Output Accuracy: ±0.4%
Digital Coupling: ±20 mV
Gain and Offset Drift: ±10 ppm/°C of 5 V FSR; and ±5μV/°C offset drift
Digital I/O Number: 8 non-latching inputs and 8 latching outputs at 8 bi-directional screw terminals
Input Levels:
VIH = 3.2 Vmin to 12 Vmax;
VIL = 1.0 Vmax to -12 Vmin
IIH = -200 μA, Vi = 3.2 V;
IIL = -0.5 mA max.
Output Levels:
VOH = 2 V min to 5 V max;
IOH = -.5 mA max.
IOL = 500 mA max, VO=1.7 V;
IOL = 50 mA max, VO = 0.7 V

OMEGA's Precision Interchangeable Thermistors

Construction - Thermistors are manufactured from oxides of nickel, manganese, iron, cobalt, magnesium, titanium and other metals. All are available epoxy encapsulated and color coded, with two 3" leads.



Thermistors with 0.2°C interchangeability also are available encased in a 2" long waterproof Teflon® tube; order by adding 100 to the part number. For example: 44005 is a standard 3000 Ω thermistor; 44105 is a Teflon® encased thermistor with the same temperature/resistance values. Stiff wire is placed in the tube so that, with slight finger pressure, it can be bent to any configuration. For Teflon® encased thermistors, consult the factory.

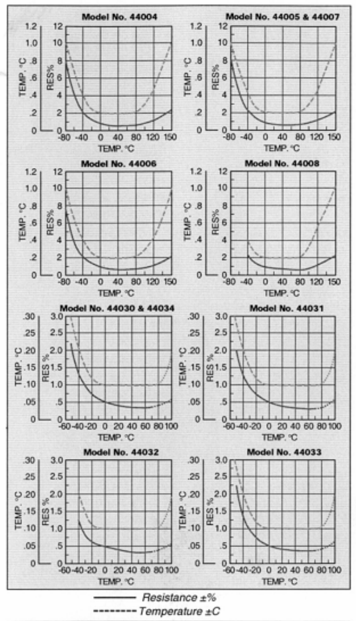
Stability - Finished thermistors are chemically stable and not significantly affected by aging or exposure to strong fields of hard nuclear radiation.

Time Constant -The time required for a thermistor to indicate 63% of a newly impressed temperature is called the time constant. For a thermistor suspended by its leads in a "well stirred" oil bath, it is 1 sec. max., or 2.5 sec. max. for Teflon® encased thermistors, and in still air it is 10 sec. max., or 25 sec. max. for Teflon® units.

Dissipation Constant - The power in milliwatts required to raise a thermistor 1°C above the surrounding temperature is the dissipation constant. For all thermistors suspended by their leads in a "well stirred" oil bath, it is 8 mw/°C min., or 1 mw/°C min. in still air.

Operating Temperature -Maximum operating temperature is 150°C. Long-term stability studies show that extended operation or continued cycling above 90°C will cause thermistors with values less than 2252 ohms at 25°C to exceed tolerances eventually. Thermistors 44030, 44031, 44032 and 44033 are designed for operation below 75°C. They will operate safely up to 100°C, but extended use above 75°C may cause a change in resistance. Storage temperature for thermistors is from -80 to 120°C.

Tolerance Curves- The following curves indicate conformance to standard resistance-temperature values as a % of resistance and as a maximum interchangeability error expressed as temperature.



Thermistor Equation

Occasionally, it is advantageous to have a general mathematical expression for a thermistor. OMEGA finds the following equation best represents thermistor behavior:

$$\frac{1}{T} = A + B\,(LOG_eR) + C(LOG_eR)^3$$

Where T = °Kelvin; R = resistance; A, B, C = fitting constants.

A, B and C may be found by writing three equations utilizing three known data sets: R1, T1; R2, T2; R3, T3; and solving for A, B, and C.

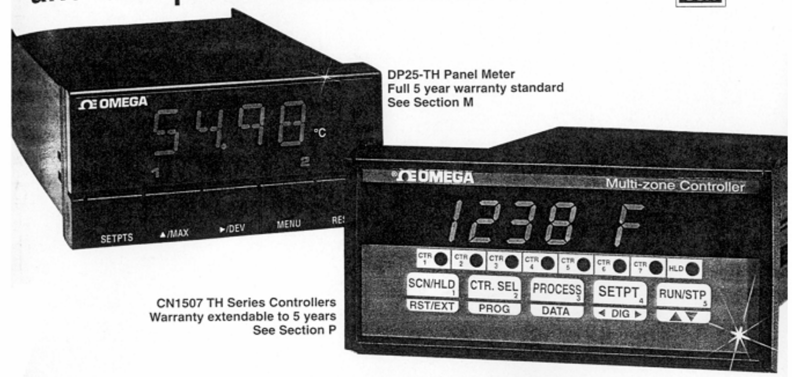
When $-40°C \le T1, T2, T3 \le 150°C$ and $| T2 - T1 | \le 50°C$, $| T3 - T2 | \le 50°C$ interpolation data generated by this equation will be accurate to ±0.01°C or better.

D-3

Thermistor Elements

and Compatible Instrumentation

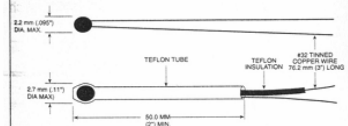
MADE IN USA



DP25-TH Panel Meter
Full 5 year warranty standard
See Section M

CN1507 TH Series Controllers
Warranty extendable to 5 years
See Section P

44000 Series Thermistor Elements



Individual Precision Interchangeable Sensors, Available ±0.2°C & ±0.1°C Accuracy

Epoxy encapsulated, precision matched to standardized resistance temperature curves, providing predicted temperature accuracy based on resistance values and tolerances shown. For Teflon® encased elements, change the middle digit to a "1", and increase price by $18 for 0.2°C interchangeable elements or $49 for 0.1°C interchangeable elements.

***Ordering Example:* 44104** *sensor, $15 + $18 = $33*

	Model Number	Resistance @ 25°C (Ohms)	Maximum Working Temp	Storage & Working Temp. for Best Stability	Price Each
±0.2°C Interchangeability 0-75°C	**44004**	2,252	150°C (300°F)	80 to +120°C (-110 to 250°F)	$15
	44005	3,000	150°C (300°F)	-80 to +120°C (-110 to 250°F)	15
	44007	5,000	150°C (300°F)	-80 to +120°C (-110 to 250°F)	15
	44006	10,000	150°C (300°F)	-80 to +120°C (-110 to 250°F)	15
	44008	30,000	150°C (300°F)	-80 to +120°C (-110 to 250°F)	15
±0.1°C Interchangeability 0-75°C	**44033**	2,252	75°C (165°F)	-80 to +75°C (-110 to 165°F)	22
	44030	3,000	75°C (165°F)	-80 to +75°C (-110 to 165°F)	22
	44034	5,000	75°C (165°F)	-80 to +75°C (-110 to 165°F)	22
	44031	10,000	75°C (165°F)	-80 to +75°C (-110 to 165°F)	22
	44032	30,000	75°C (165°F)	-80 to +75°C (-110 to 165°F)	22

Typical Thermometric Drift (±0.2°C Elements)

Operating Temp.	10 months	100 months
0°C	<0.01°C	<0.01°C
25°C	<0.01°C	0.02°C
100°C	0.20°C	0.32°C
150°C	1.5°C	not recommended

Discount Schedule	
1-9	Net
10-24	10%
25-49	20%
50-99	30%
100 & over	40%

For Sales and Service, Call:

1-800-82-66342®
1-800-TC-OMEGA

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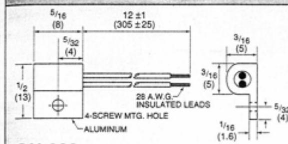
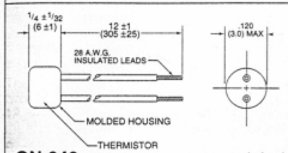
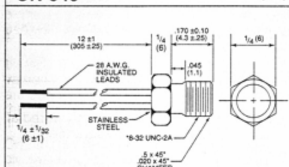
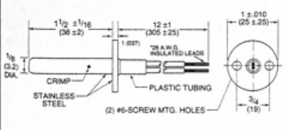
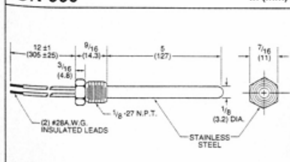
NOTE: OMEGA's Precision Interchangeable Probes are normally constructed with ±0.2°C Interchangeable Thermistors. These are Types 44004, 44005, 44007, 44006 and 44008. If assemblies are required with ±0.1°C Interchangeable Probes, change the portion of the model number designation to reflect the ±0.1°C Thermistor. Example: ON-901-44004 becomes ON-901-44033. Add $11 to the designated Model price for ±0.1°C Interchangeable Thermistors. Interchangeable Thermistors with ±0.1°C Interchangeability are Types 44033, 44030, 44034, 44031 and 44032

MOST POPULAR MODELS HIGHLIGHTED!

To Order *(Specify Model Number)*

Dimensions and Materials	Description and Typical Application	Model Number	Resistance (ohms) @ 25°C
 **ON-930** in (mm)	**Epoxy Encapsulated Thermistor Sensor in Screw Mounted Aluminum Housing with Teflon® Insulated Leads.** **Surface sensor assembly:** designed for a variety of temperature measurement and control applications. It represents a low cost, fast response unit and lends itself to easy mounting on flat surfaces. **Leads:** 300 mm (12") **Maximum temperature:** 100°C (212°F) Body Type ON-930 $44 **All prices include sensor**	ON-930-44004	2,252
		ON-930-44005	3,000
		ON-930-44007	5,000
		ON-930-44006	10,000
		ON-930-44008	30,000
 **ON-940** in (mm)	**Encapsulated Thermistor Sensor in Molded Housing with Teflon® Insulated Leads.** **Insertion sensor assembly:** specifically designed for high reliability, high volume, and low cost applications where fast time response and small size are determining factors. The unit is easily affixed by inserting in a small hole for mounting. **Leads:** 300 mm (12") **Maximum temperature:** 100°C (212°F) Body Type ON-940 $42 **All prices include sensor**	ON-940-44004	2,252
		ON-940-44005	3,000
		ON-940-44007	5,000
		ON-940-44006	10,000
		ON-940-44008	30,000
 **ON-950** in (mm)	**Stainless Steel Housing with ¼" Hex. Head and #8-32 NC-2A Threaded Body. Thermistor Sensor Epoxy Encapsulated in Housing with Teflon® Insulated Leads.** **Surface sensor assembly:** for temperature measurement and control where design problems require stability against vibration and shock. The unit has been designed for temperature control and measurement problems where low cost and reliability are crucial. **Leads:** 300 mm (12") **Maximum temperature:** 100°C (212°F) Body Type ON-950 $43 **All prices include sensor**	ON-950-44004	2,252
		ON-950-44005	3,000
		ON-950-44007	5,000
		ON-950-44006	10,000
		ON-950-44008	30,000
 **ON-960** in (mm)	**Closed-End Stainless Steel Tube with Thermistor Sensor Mounted in Tip. Stainless Steel Mounting Plate with (2) Two Mounting Holes Welded to Tube. Teflon® Insulated Leads.** **Air flow sensor assembly:** designed to satisfy the many requirements of air temperature-measurement and control in Air Conditioning systems and equipment cooling systems. The unit lends itself to easy mounting to standard metal ducting. **Leads:** 300 mm (12") **Maximum temperature:** 100°C (212°F) Body Type ON-960 $44 **All prices include sensor**	ON-960-44004	2,252
		ON-960-44005	3,000
		ON-960-44007	5,000
		ON-960-44006	10,000
		ON-960-44008	30,000
 **ON-970** in (mm)	**Stainless Steel Housing with 7/16" Hex. Head and 1/8-#27 NPT Threaded Body. Thermistor Sensor Epoxy Encapsulated in Housing with Teflon® Insulated Leads.** **Liquid immersion fluid sensor assembly:** ideal for obtaining temperature measurement and control readings in pipes or closed vessels within pressurized systems. Threaded hex. head design affords greater resistance to shock and vibration when mounted. Leads 12" standard, other lengths available, consult factory. **Leads:** 300 mm (12") **Maximum temperature:** 100°C (212°F) Body Type ON-970 $55 **All prices include sensor**	ON-970-44004	2,252
		ON-970-44005	3,000
		ON-970-44007	5,000
		ON-970-44006	10,000
		ON-970-44008	30,000

D-10

OMEGABOND® High Temperature

Air Set Cements

- Heat Conductive
- Thermal Shock Resistant
- Insulate Electricity
- Resists Oils, Solvents, Most Acids
- Adheres to Practically All Clean Surfaces **

From **$36**

Air Set Cements set or cure through loss of moisture by evaporation. Atmospheric conditions therefore affect the drying rate. Air Set Cements are used mainly in thin film applications (applied in thicknesses less than ¼")*.

SELECTION CRITERIA FOR CEMENTS

1. **Type of Application** – Potting, sealing, encapsulating, assembling, bonding. Is a thick or thin film of cement required? This dictates whether or not an air set or a chemical set cement should be used.
2. **Thermal Considerations** – What is the maximum temperature that the cement must withstand? What degree of thermal conductivity is needed? What degree of thermal expansion is allowed? These parameters are then matched to the appropriate cement.
3. **Substrate** – What materials will the cement be in contact with?
4. **Application Considerations** – Pot life, set time, method of dispensing, batch size, cure procedure.
5. **Miscellaneous Considerations** – Porosity, moisture absorption, electrical resistance, volume stability, clearances/tolerances.

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

Model No.	Price	Description
OB-300	$36	OMEGABOND® 300 Powder, 8 fluid oz (one part cement; just mix with water)
OB-400	36	OMEGABOND® 400 Powder, 8 fluid oz (one part cement; just mix with water)
OB-500 POWDER	36	OMEGABOND® 500 Powder, 8 fluid oz (Two part cement; mix powder with OB-500 Liquid)
OB-500 liquid	36	OMEGABOND® 500 Liquid, 8 fluid oz (Two part cement; mix liquid with OB-500 Powder)
OB-KIT-1	54	Air Set Cement Kit. Ideal for research purposes. Includes 2 fluid oz each of OB-300, OB-400, OB-500 Powder and OB-500 Liquid
OB-TL	36	OMEGABOND® Thinning Liquid, 8 fluid oz used to dampen porous substrates before application of mixed OB-300 or OB-400 cements

Ordering Example: *OB-400 is a high temperature air set cement, 8 fluid oz.,* ***$36***

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Applications:

OMEGABOND® 300
- Assembling
- Sealing
- Insulating

OMEGABOND® 400
- Coating
- Embedding
- Insulating

OMEGABOND® 500
- Coating
- Dipping
- Casting

Physical Properties

	OMEGABOND 300	OMEGABOND 400	OMEGABOND 500
Type of Cement (One or Two Part)	One Part	One Part	Two Part
Coefficient of thermal expansion, in/in°F	6.2 x 10^{-6}	13.0 x 10^{-6}	10.93 x 10^{-6}
Color	Off White	Tan to Gray	Off White
Compressive strength, PSI	3900	3300	1500††
Dielectric constant	3.5 - 6.0	3.4 - 4.5	
Dielectric strength at 70°F, Volts/mil	12.5 to 51.0	12.5 to 51.0	
Dielectric strength at 750°F, Volts/mil	≤15.0	≤15.0	
Dielectric strength at 1475°F, Volts/mil	≤1.3	≤1.3	
Maximum service temperature, °F	1800	2600	2200
Modulus of rupture, PSI	460		
Shear strength, PSI	710	375	
Tensile strength, PSI	410	325	1500
Volume resistivity at 70°F, ohm-cm	10^8-10^9	10^8-10^9	
Volume resistivity at 750°F, ohm-cm	10^4-10^5	10^5-10^6	
Volume resistivity at 1475°F, ohm-cm	10^2-10^3	10^3-10^4	
Density (Wet), lbs/ft³			112
Density (Dry), lbs/ft³			82
Flexural strength, PSI			2000††
Modulus of Elasticity, PSI			3.6 x 10^5
Pot Life, hr			1.0
Thermal Conductivity, Btu-in/ft²-hr-°F	4-6	11	
Mix Ratio	One-Part Cement: Just mix powder with water to a smooth, uniform consistency.	One-Part Cement: Just mix powder with water to a smooth, uniform consistency.	Two-Part Cement: Just mix powder and binder. Mix ratio for cast applications ranges from 1.87-2.0 parts powder to 1 part liquid binder by weight.
Curing Schedule	OMEGABOND 300® cures at room temperature by air drying in 18-24 hours, depending upon thickness and consistency. Cure time can be accelerated by low temperature oven drying at 180°F. If the cement is to be exposed to elevated temperatures, cure for 18-24 hours at ambient temperature, then oven dry for 4 hours at 180°F and for an additional 4 hours at 220°F. This helps to prevent spilling.	OMEGABOND 400® cures at room temperature by air drying in 18-24 hours, depending upon thickness and consistency. Cure time can be accelerated by low temperature oven drying at 180°F. If the cement is to be exposed to elevated temperatures, cure for 18-24 hours at ambient temperature, then oven dry for 4 hours at 180°F and for an additional 4 hours at 220°F. This helps to prevent spilling.	OMEGABOND 500® has a pot life of 1 hour after the powder and binder are mixed together. OB-500 reaches an initial air set after 4 hours at room temperature. A final set is only reached after oven baking at 130°F for 4 hours. If the cement is to be used at temperatures above 212°F, OB-500 must under go an extended cure at 220°F or above for 12 hours.
Distinguishing Characteristics and Applications	Lower thermal conductivity and coefficient of thermal expansion.	Higher thermal conductivity and coefficient of thermal expansion. High maximum temperature rating.	Withstands short-term immersion in molten metal. Used as a coating on expendable thermocouple tubes.

†These physical properties were determined under laboratory conditions using applicable ASTM procedures. Actual field data may vary. Do not use physical properties data for specifications.

†† Strength at 1 day after curing at 220°F

** Chemical Set Cements are also available. See OMEGABOND® 600, OMEGABOND® 700 and CC High Temperature Cement. These cements set or cure by an internal chemical action which does not require exposure to air. They can be used in thick applications (greater than ¼" thickness).*

*** Porous substrates may require dampening with Thinning Liquid before application of mixed cement. For OMEGABOND® 300 and OMEGABOND® 400 (one part cements), order OMEGABOND® Thinning Liquid, Model No.* ***OB-TL****, Price* ***$36*** *(8 fluid oz). For OMEGABOND® 500 (two part cement), use OMEGABOND® 500 Liquid to dampen porous substrates.*

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OMEGABOND® High Temperature Chemical Set Cements

MADE IN USA

- Heat Conductive
- Thermal Shock Resistant
- Insulate Electricity
- Resists Oils, Solvents, Most Acids
- Adhere To Practically All Clean Surfaces **

From **$18**

Chemical Set Cements set or cure by an internal chemical action which does not require exposure to air. Chemical Set Cements can be used in thick applications (applied in thicknesses greater than ¼")*.

SELECTION CRITERIA FOR CEMENTS

1. **Type of Application** – Potting, sealing, encapsulating, assembling, bonding. Is a thick or thin film of cement required? This dictates whether or not an air set or a chemical set cement can be used.
2. **Thermal Considerations** – What is the maximum temperature that the cement must withstand? What degree of thermal conductivity is needed? What degree of thermal expansion is allowed? These properties are then matched to the appropriate cement.
3. **Solvent** – 10% Sodium Hydroxide. However it's difficult to remove cured cement.
4. **Substrate** – What materials will the cement be in contact with?
5. **Application Consideration** – Pot life, set time, method of dispensing, batch size, cure procedure.
6. **Miscellaneous Considerations** – Porosity, moisture absorption, electrical resistance, volume stability, clearances/tolerances.

To Order (Specify Model Number)

Model No.	Price	Description
OB-600	$36	OMEGABOND® 600 Powder, 8 fluid oz (one part cement; just mix with water)
OB-700	36	OMEGABOND® 700 Powder, 8 fluid oz (one part cement; just mix with water)
CC HIGH TEMP	18	CC High Temperature Cement Kit, contains 2.25 oz powder and 0.75 oz liquid by weight
CC Filler	36	CC High Temperature Cement Powder, 8 oz by weight (Two part cement; mix liquid with CC Binder)
CC Binder	36	CC High Temperature Cement Liquid, 8 oz by weight (Two part cement; mix liquid with CC Filler)
OB-KIT-2	54	Chemical Set Cement Kit. Ideal for research purposes. Includes 2 fluid oz. each of OB-600 and OB-700 and also one CC High Temp Kit
OB-TL	36	OMEGABOND® Thinning Liquid, 8 fluid oz used to dampen porous substrates before application of mixed OB-300 or OB-400 cements

Ordering Example: ***OB-KIT-2*** *is a chemical set cement kit containing OB-600, OB-700, and one CC High Temp Kit,* ***$54.***

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APPLICATIONS:

OMEGABOND® 600
- Potting
- Bonding
- Insulating
- Embedding
- Coating

OMEGABOND® 700
- Coating
- Assembling
- Sealing

CC High Temperature Cement
- Cementing on and Insulating Thermocouples for Surface Temperature Measurement

Physical Properties†

Cement	OMEGABOND 600	OMEGABOND 700	CC High Temperature
Type of Cement (One or Two Part)	One Part	One Part	Two Part
Coefficient of thermal expansion, in/in/°F	2.6×10^{6}	12.4×10^{6}	4.6×10^{6}
Color	Off White	White	Tan
Compressive strength, PSI	4500-5500	3500	3900
Density, lbs/ft³	160		141
Dielectric constant	3.0 - 4.0		5.0 to 7.0
Dielectric strength at 70°F, Volts/mil	76.0 to 101.0		25.0 to 51.0
Dielectric strength at 750°F, Volts/mil	25.0 to 38.0		12.5 to 25.0
Dielectric strength at 1475°F, Volts/mil	12.5 to 25.0		≤1.3
Maximum service temperature, °F (°C)	2600 (1426)	1600 (871)	1550 (843)
Modulus of rupture, PSI	450		
Tensile strength, PSI	250		425
Volume resistivity at 70°F, ohm-cm	10^{10}-10^{11}		10^{7}-10^{9}
Volume resistivity at 750°F, ohm-cm	10^{9}-10^{10}		10^{4}-10^{6}
Volume resistivity at 1475°F, ohm-cm	10^{8}-10^{9}		10^{2}-10^{3}
Flexural strength, PSI		435	
Absorption, %			10 - 12
Shrinkage, %			0.5
Thermal Conductivity, Btu-in/ft²-hr-°F	10 - 12	4.5 to 5.9	8
Mix Ratio	Mix 100 Parts powder with 13 parts water by weight.	Mix 75-80% powder with 20-25% water by weight.	Mix 3 parts powder to 1 part liquid by weight, or 2 parts filler to 1 part liquid by volume.
Curing Schedule	OMEGABOND 600® cures at room temperature by internal chemical action in 18-24 hours. Cure time can be accelerated by low temperature oven drying at 180°F. If the cement is to be exposed to elevated temperatures, cure for 18-24 hours at ambient temperature, then oven dry for 4 hours at 180°F and for an additional 4 hours at 220°F. This helps to prevent spilling.	OMEGABOND 700® cures at room temperature with a chemical set action in 18-24 hours, Cure time can be accelerated by low temperature oven drying at 180°F. If the cement is to be exposed to elevated temperatures, cure for 18-24 hours at ambient temperature, then oven dry for 4 hours at 180°F and for an additional 4 hours at 220°F. This helps to prevent spilling.	CC High Temperature Cement hardens with an internal chemical-setting action with an initial set in approximately 30 minutes. The final set is reached in 18 to 24 hours when cured at room temperature. If it is desired to accelerate the curing time, set the drying oven to 150°F and the cement will cure in 4 hours. If the drying oven is set to 220°F, the cement will cure in 3 hours.
Distinguishing Characteristics and Applications	High dielectric strength. Used to pot nickel chromium resistance heating wire. Won't stick to smooth quartz.	Used on metals or other materials which have a high coefficient of thermal expansion. Excellent bonding characteristics.	Used to cement on and insulate thermocouples for surface temperature measurement.

†These physical properties were determined under laboratory conditions using applicable ASTM procedures. Actual field data may vary. Do not use physical properties data for specifications.

** Air Set Cements are also available See OMEGABOND® 300, OMEGABOND® 400 and OMEGABOND® 500. These cements set or cure through loss of moisture by evaporation. Atmospheric conditions therefore affect the drying rate. Air Set Cements are used mainly in the thin film applications (less than ¼" thickness.)*

*** Porous substrates may require dampening with Thinning Liquid before application of mixed cement. For OMEGABOND® 600 and OMEGABOND® 700 (one part cements), order OMEGABOND® Thinning Liquid, Model No.* ***OB-TL****, Price* ***$36*** *(8 fluid oz). For CC High Temperature Cement, use CC High Temperature Cement Liquid Binder to dampen porous substrates.*

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High Temperature and High Thermally Conductive Epoxies

OMEGABOND® epoxy and OMEGATHERM® thermal conducting paste are high temperature and high thermally conductive epoxies and silicone products. They are specially formulated for permanent and temporary bonding of thermocouples, thin film RTDs, thermistors and other temperature sensors, to most surfaces–metals, ceramics, glass, plastics, paper products.

OMEGABOND® and OMEGATHERM® products are compounded and packaged for convenient, easy mixing and application. Each formulation exhibits important characteristics necessary for accurate, fast, reliable temperature measurement. These are: good adhesion and strength, high temperature rating, high thermal conduction, high electric insulation, thixotropic consistency, fast cure, and easy application.

To assist in your selection, a summary of each product's properties is shown in the accompanying table.

"Twin pak" packaging is supplied to ensure the user with accurate proportioning of resin and catalyst, as well as to provide a clean, fast means of mixing. The "Twin Pak" is a flexible, transparent plastic pouch, separated into two isolated compartments by means of a removable external divider. In one compartment is the resin, the other the pre-measured catalyst. To use, remove the divider, mix the two components by kneading the pouch, then snip off a corner to dispense. Each "Twin Pak" comes with an instruction sheet, enclosed in a clear, heat-sealed plastic envelope.

Typical Properties

Model No.	OB-100	OB-101	OB-200	OB-201
Material	Fast Set Epoxy Adhesive	Epoxy Adhesive	Epoxy Adhesive	Silicone Grease
Continuous Temperature	265°F (130°C)	221°F (105°C)	500°F (260°C)	392°F (200°C)
Cure	8–12 min. set Room Temp.	Room Temp.	Elevated Temp.	Not required
Adheres to Most*	M, C, PL, PA, W	M, C, PL, PA, W	M, C, PL, PA, W	Wets most Surfaces
Thermal conductivity (k) (BTU) (in)/(hr) (ft^2) (°F)	Low	High 7.2	Very High 9.6	Extremely High 16
Electrical Insulation Volume Resistivity ohm–cm	High 10^{12}	Very High 10^{15}	Very High 10^{15}	Very High 10^{14}
Tensile Shear PSI MIN	2000	2200	2700	—
Flexure Strength PSI MIN		12,000	17,000	
Coefficient of Thermal Expansion in/in/°F	51×10^{-6}	20×10^{-6}	21×10^{-6}	

*M=Metal, C=Ceramic, PL=Plastic, PA=Paper Products, W=Wood

The above information, while determined by tests and evaluation, is offered only as a general guide. Actual suitability for a particular purpose must be determined by material user. This information is not to be taken as a warranty for which we assume legal responsibility.

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OMEGABOND® 100

OMEGABOND® 100 — a fast (8 to 12 minute setting time), room temperature, two-part epoxy. Recommended for easy temporary and permanent bonding of beaded wire and "cement-on" thermocouples. Adheres to metals, ceramics, epoxy laminates, glass, wood, concrete and many other materials—for temperature measurements up to 265°F. It is not recommended for those endeavoring to achieve the ultimate in precision and speed of response, since this unfilled system has a relatively low thermal conductivity.

Temporary installation of beaded wire thermocouples can be achieved by using a very small amount of OMEGABOND® 100 to tack the bead to the surface and packing OMEGATHERM® 201 around the exposed surface to improve heat transfer. This clear syrup consistency—100% solid adhesive — contains no solvents and has good strength and electrical insulation characteristics. Note: The working time after mixing the two-part system at room temperature is only 6 to 8 minutes. OMEGABOND 100 is available in "Twin Pak" packs and one- and two-pound kits.

OMEGABOND® 101

OMEGABOND® 101—is a very versatile room-temperature curing, highly thermally conductive, two-part epoxy adhesive designed specifically to bond permanently "cement-on" and beaded wire thermocouples and other sensors to the widest variety of materials. Adheres to most metals, wood, ceramics, cements, paper products, and many plastics and rubbers. It is rated for continuous use at 221°F. This thixotropic off-white paste will set up in approximately four hours at room temperature with full curing in 24 hours. Curing can be accelerated by applying moderate heat.

OMEGABOND® 101 has excellent shear and tensile strength, high electrical insulation and excellent chemical and solvent resistance. It is supplied in convenient "Twin Pak" packs as well as one- and two-pound kits, and is easy to mix, apply and cure.

To Order *(Specify Model Number)*

Kit size vs Material	Model Number & Price per kit			
	OB-100-□	OB-101-□	OB-200-□	OT-201-□
"A"	OB-100-1/4 **$4** one ¼ oz. Twin Pak	OB-101-1/2 **$5** one ½ oz. Twin Pak		OT-201-1/2 **$5** one ½ oz. Jar
"B"	OB-100-1 **$12** four ¼ oz. Twin Paks	OB-101-2 **$8** one 2 oz. Twin Pak	OB-200-2 **$12** one 2 oz. Twin Pak	OT-201-2 **$7.50** one 2 oz. Jar
1 lb. Two-Can Kit	OB-100-16 **$32**	OB-101-16 **$50**	OB-200-16 **$45**	OT-201-16 **$55**
Two 1 lb. Kits				OT-201-32 **$110**

OMEGABOND® 200

OMEGABOND® 200 — is a black, high temperature, high thermally conductive, two-part epoxy system which will bond sensors to most materials, including metals, glass, ceramics and most plastics. It is recommended for bonding of "cement-on" and beaded wire thermocouples for accuracy and fast temperature measurement to 500°F. This epoxy system cures at elevated temperatures. Curing time is 8 hours at 250°F, 2 hours at 400°F. It has excellent strength and electrical insulating characteristics. Its thixotropic paste consistency virtually ensures freedom from sag during curing when applied to vertical surfaces.

OMEGABOND® 200 is mixed 100 parts resin to 10 parts catalyst by weight, and is supplied in "Twin Paks" to ensure proper formulating. One- and two-pound kits are also available.

OMEGATHERM® 201

OMEGATHERM® 201 — is a very high thermally conductive filled silicone paste, ideally suited for many temperature measurement applications. This thick, grey, smooth paste wets most surfaces and will not harden on long exposure to elevated temperatures. It is rated for continuous use between –40 and 392°F.

OMEGATHERM® 201 provides an excellent means of conducting heat and expanding the heat-path area from a surface to a temperature measurement sensor, thus increasing the speed of response and improving accuracy. Some applications are:

a) **Surface Measurement Probes —** dab a small amount on the surface and push the sensor into this area.

b) **Temporary bonding and encapsulating of temperature sensors —** simply dab OMEGATHERM® 201 onto the surface or in the cavity, plant the sensor in the paste, and tape to hold in place.

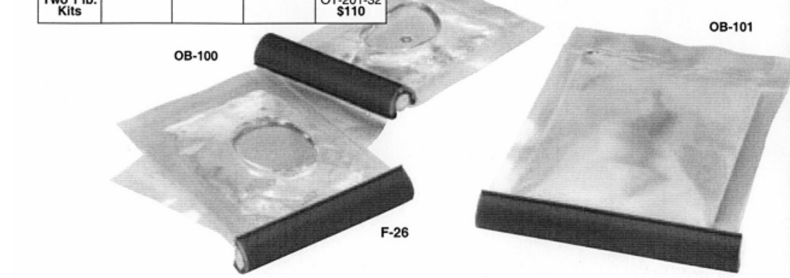
This highly versatile paste is supplied in ½- and 2-ounce jars, as well as in one- and two-pound containers.

Multi-Purpose OMEGABOND® & OMEGATHERM® Kit

This versatile kit is recommended as a convenient way to determine the best means to bond sensors before ordering in quantity. Each kit contains:

four — ¼ oz. "Twin Paks" of OMEGABOND® 100
two — ½ oz. "Twin Paks" of OMEGABOND® 101
one — 2 oz. "Twin Pak" of OMEGABOND® 200
two — ½ oz. Jars of OMEGATHERM® 201

When ordering, specify **"MPK-1"** **$30** per kit



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Appendix C

Wisconsin Department of Transportation
State Highway Maintenance Manual
Guideline 35.30
Application Rates – De-icing

A. De-icing Application Rates (4-lanes and greater)

See page 2 of 3

B. De-icing Application Rates (2-lanes)

See page 3 of 3

DE-ICING APPLICATI ON RATES FOR PRE-WETTED SALT – (4-LANES AND GREATER)

This guide is not meant to bea substitutefor the useof judgment and theobservation of the result of treatments on existingconditions. It is meant to showvariables that usually occur together and thetreatment that hasproven to bethemost successful. Thisguide should then be used to assist in deciding on the best fitting courseof action dependingon existing conditions

WEATHER CONDITIONS		SALT APPLICATION RATE (Pounds of Material Per Lane Mile of Pavement)	REMARKS
PAVEMENT TEMPERATURE	PRECIPITATION		
28 F AND ABOVE	Snow	Initial at 200 lbs of Salt Repeat at 100-200 lbs of Salt	Allow de-icing agents time to begin working before making additional plowing passes. If sufficient moisture is present, dry salt without pre-wetting can be applied.
	Sleet/Freezing Rain		Allow de-icing agents time to begin working before making additional plowing passes. If sufficient moisture is present, dry salt without pre-wetting can be applied.
23-28 F	Snow/Sleet	Initial at 100-300 lbs of Salt Repeat at 100-200 lbs of Salt	Allow de-icing agents time to begin working before making additional plowing passes. If sufficient moisture is present, dry salt without pre-wetting can be applied.
	Freezing Rain	Initial at 200-400 lbs of Salt Repeat at 100-200 lbs of Salt	Allow de-icing agents to begin working before making additional plowing passes. Consider using prewetted salt/sand mix for repeat applications
15-23 F	Dry Snow	Plow Only	Hazardous areas may be treated with abrasives/deicing agents
	Wet Snow/Sleet	Initial at 200-400 lbs of Salt Repeat at 100-300 lbs of Salt	Allow de-icing agents time to begin working before making additional plowing passes. Consider using prewetted salt/sand mix for repeat applications If sufficient moisture is present, dry salt without pre-wetting can be applied
Below 15 F	Dry Snow	Plow Only	Hazardous areas may be treated with abrasives/deicing agents
	Ice/Snow Pack	200-400 lbs salt, sand/salt mix, or salt mixed dry calcium chloride	Allow de-icing agents to begin working before making additional plowing passes.

Notes:

1. Mechanical means ofsnow removal is the preferred method. Before applying anyde-icingagent, the surface should be cleared of as much snow and ice as possible.
2. Application rates listed above are "maximum recommended rates". The operator should strive to apply only the amountof salt/de-icing agents necessary to accomplish the desiredlevel of service. Rates mayvary with regard to pavement temperature, type of pavement, and weather conditions.
3. This table assumes the salt is prewetted.
4. Ground speed controllers should be calibrated annuallyor more often as necessary to assure that preset applicationrates are within acceptable levels.
5. When wind speed is over 15 mph, use caution when salting.
6. Consider the maintenance section cycle time when determining application rates.

DE-ICING APPLICATION RATES FOR PRE-WETTED SALT – (2-LANES)

This guide is not meant to be a substitute for the use of judgment and the observation of the result of treatments on existing conditions. It is meant to show variables that usually occur together and the treatment that has proven to be the most successful. This guide should then be used to assist in deciding on the best fitting course of action depending on existing conditions.

WEATHER CONDITIONS		SALT APPLICATION RATE (Pounds of Material Per Lane Mile of Pavement)	REMARKS
PAVEMENT TEMPERATURE	PRECIPITATION		
28 F AND ABOVE	Snow	Initial at 200 of Salt Repeat at 100-200 of Salt	Allow de-icing agents time to begin working before making additional plowing passes. If sufficient moisture is present, dry salt without pre-wetting can be applied.
	Sleet/Feezirg Rain		Allow de-icing agents time to begin working before making additional plowing passes. If sufficient moisture is present, dry salt without pre-wetting can be applied.
23-28 F	Snow/Sleet	Initial at 100-300 of Salt Repeat at 100-200 of Salt	Allow de-icing agents time to begin working before making additional plowing passes. If sufficient moisture is present, dry salt without pre-wetting can be applied.
	Freezing Rain	Initial at 100-300 of Salt Repeat at 100-200 of Salt	Allow de-icing agents time to begin working before making additional plowing passes. Consider using prewetted salt/sand mix for repeat applications
15-23 F	Dry Snow	Plow Only	Hazadous aeas may be treated with abrasives/deicing agents
	Wet Snow/Sleet	Initial at 100-300 of Salt Repeat at 100-200 of Salt	Allow de-icing agents time to begin working before making additional plowing passes. Consider using prewetted salt/sand mix for repeat applications If sufficient moisture is present, dry salt without pre-wetting can be applied
Below 15 F	Dry Snow	Plow Only	Hazadous aeas may be treated with abrasives/deicing agents
	Ice/Snow Pack	100-300 lbs salt, sand/salt mix, or salt mixed with dry Calcium Chloride	Allow de-icing agents time to begin working before making additional plowing passes.

Notes:

1. Mechanical means of snow removal is the preferred method. Before applying any de-icing agents, the roadway surface should be cleared of as much snow and ice as possible by mechanical means.
2. Application rates listed above are "maximum recommended rates". The operator should strive to apply only the amount of salt/de-icing agents necessary to accomplish the desired level of service. Rates may vary with regard to pavement temperature, type of roadway surface, and weather conditions.
3. This table assumes the salt is prewetted.
4. Ground speed controllers should be calibrated annually or more often as necessary to assure that preset application rates are within acceptable levels.
5. When wind speed is over 15 mph, use caution when salting.
6. Consider the maintenance section cycle time when determining application rates.

Anti-icing Guidelines

PREDICTED PRECIPITATION EVENT	Recommended Locations	Application Rate: Liquid (gal/lane-mi.)	Application Rate: Pre-wetted Salt (lb/lane-mi)	COMMENTS
Frost or Black Ice	Bridge Decks and Trouble Spots	20-30 (frost) 30-40 (Black Ice)	50-150	1) Consider treating approaches as well as bridge decks. 2) Treat ice patches, if needed, with pre-wetted salt at 100 lb/lane-mi.
Sleet	Bridge Decks and Trouble Spots and Intersections	20 Recommended 30 Maximum	200-400(4) 100-300(5)	1) Consider treating approaches as well as bridge decks. 2) Treat ice patches, if needed, with pre-wetted salt at 100 lb/lane-mi.
Freezing Rain	Any area of concern	Not Recommended	200-400(4) 100-300(5)	It is not recommended to apply liquid de-icing agents in an anti-icing mode prior to freezing rain events.
Light Snow (< 1/2" in./hr.)	Trouble Spots and Intersections	30 Recommended 40 Maximum	100-200	If anti-icing is performed prior to a snow event, re-application may be necessary to prevent re-freeze. It also may be necessary to switch to a de-icing mode.
Moderate or Heavy Snow (≥ 1/2 in./hr)	Trouble Spots and Intersections	40 Recommended 50 Maximum	100-300	1) Do not apply liquid anti-icing agents onto heavy snow accumulation or packed snow. 2) Applications will need to be more frequent at lower temperatures and higher snowfall rates. 3) If anti-icing is performed prior to a snow event, re-application may be necessary to prevent re-freeze. It also may be necessary to switch to a de-icing mode.

Notes:

(1) Anti-icing operations typically should be conducted during normal, non-overtime working hours.

(2) It is not recommended to apply de-icing agents in an anti-icing mode when the pavement temperature is below 20℉ or drifting is a problem.

(3) Time initial anti-icing agent applications and subsequent de-icing agent applications to prevent deteriorating conditions or development of packed and bonded snow.

(4) 4-Lanes and Greater

(5) 2 Lanes

Appendix D

Statistical Significance Results

Statistical Significance Summary - Laboratory

Test Description:	Fixed Temperature 5º C		Fixed Temperature 0º C		Fixed Temperature -6º C		Fixed Temperature -17º C		Declining Temperature		Increasing Temperature	
TEST NO.	1-1a**		1-1b**		1-1c**		1-1d**		1-2a		1-2b	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.16	0.24	0.03	0.12	1.06	1.23	0.11	0.06	1.74	4.75*	1.52	2.91*
BOSCHUNG	1.82	0.19	0.20	0.16	0.22	0.19	0.06	0.06	1.22*	0.26	1.10*	0.36
LUFFT	0.21	0.08	0.11	0.03	0.10	0.05	0.53	0.40	0.36	0.42	0.55	0.35
POINT 6	1.60	0.89	0.38	0.74	0.20	0.07	0.23	0.27	0.54	0.29	1.43*	1.17*
SSI	0.45	0.49	0.40	0.30	0.73	0.58	0.74	0.60	1.23*	0.97	0.14	0.15
VAISALA	0.13	0.12	0.08	0.11	0.07	0.12	0.08	0.05	0.13	0.19	1.16	0.14
SPRAGUE	0.78	0.52	1.13	0.36	1.53	0.46	1.56	0.33	N/A	0.98	N/A	0.68
CONTROL PRODUCTS	0.20	0.20	0.08	0.10	0.55	0.30	1.20	0.31	N/A	0.75	N/A	0.70

Test Description:	Cold Pavement w/o Solar Impact		Cold Pavement w/ Solar Impact		Warm Pavement w/ Snowfall		Cold Pavement w/ Rainfall		Iced Pavement w/ Rainfall		Compacted Snow (melting)	
TEST NO.	1-5a**		1-5b		1-6		1-7		1-8		1-9	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.31	0.31	3.35*	3.17*	1.34*	1.05*	0.85*	0.62	0.43*	0.58	1.20*	0.56
BOSCHUNG	0.17	0.16	0.97*	0.55*	0.85	0.32	0.65	0.63	0.44	0.34	0.88*	0.56*
LUFFT	0.16	0.06	0.23*	0.16	0.46	0.15	0.90*	0.92*	0.31	0.30	0.55	0.60
POINT 6	0.28	0.19	0.68*	1.47*	0.76	0.67	1.27*	0.74*	0.97*	0.77*	0.61	1.12*
SSI	0.50	0.54	2.10*	1.52*	0.55	0.47	1.42*	1.17*	0.67*	1.09*	0.39	0.76
VAISALA	0.07	0.08	3.35*	1.23*	0.79	0.76	1.17	0.75	0.89	0.62	N/A	N/A
SPRAGUE	1.13	0.47	1.15	N/A	1.01*	0.37	1.96*	N/A	1.98*	0.83*	1.39	0.63
CONTROL PRODUCTS	0.10	0.15	2.80*	0.63*	0.56	0.71	0.95*	0.49	0.67*	0.42	1.76*	0.87

Test Description:	Frost Depositing		NaCl: Cold w/o Solar Impact		NaCl: Cold w/ Solar Impact		NaCl: Warm w/ Snow		NaCl: Cold w/ Rainfall		NaCl: Iced Pavement w/ Rainfall	
TEST NO.	1-10		2-1a**		2-1b		2-2		2-3		2-4	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.66*	0.62*	0.09	0.05	2.14*	1.68*	1.58*	1.06*	0.50*	0.51	0.67*	0.52
BOSCHUNG	0.52*	0.22	0.22	0.18	0.51	0.46*	0.28	0.63	0.37	0.26	0.45	0.26
LUFFT	0.37	0.24	0.10	0.10	0.31*	0.37*	1.10*	0.28	0.60*	0.59*	N/A	N/A
POINT 6	1.27*	N/A	0.18	0.14	1.76*	1.17*	0.72	0.57	1.08	0.56*	1.34*	0.74*
SSI	0.38*	0.32	0.62	0.43	2.62*	1.44*	0.44	0.51	0.68*	0.77*	1.10*	0.97*
VAISALA	0.20	0.14	N/A	N/A	2.15*	1.16*	0.71	0.60	0.34	0.48	0.38	0.54
SPRAGUE	1.21*	N/A	0.82	N/A	0.71*	N/A	0.94*	N/A	1.27*	N/A	2.02*	N/A
CONTROL PRODUCTS	0.80*	0.51*	0.30	0.16	2.61*	0.20	0.93*	1.06*	0.54*	0.39	0.39	0.38

1. Values in table are Mean Absolute Differences between sensor and baseline temperature in Degrees Celsius
2. Values labeled with an "*" indicate that the difference between the sensor and baseline data is statistically significant
3. Tests labeled with an "**" indicate that there were too few data points to perform a statistical significance test
4. N/A represents test data not available, see test result section for more detailed explanation

Statistical Significance Summary - Field

Test Description:	Cold Day w/ Solar Impact		Cold Day w/o Solar Impact		Cold Night w/o Radiation Cooling		Cold Night w/ Radiation Cooling	
TEST NO.	3-1a		3-1b		3-2a		3-2b	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.39	1.66*	N/A	N/A	0.09*	0.17*	0.44*	0.39*
BOSCHUNG	0.58	2.05*	0.29	0.92*	0.76*	0.74*	0.61*	1.01*
LUFFT	0.23	1.85*	0.10	1.07*	0.63*	0.87*	0.91*	1.37*
SSI	0.58	1.31*	0.50	0.68*	0.30*	0.74*	0.08	0.46*
VAISALA	1.49	2.25	0.94	1.37	0.98*	0.94*	1.09*	1.01*

Test Description:	Warm Pavement w/ Snowfall		Cold Pavement w/ Rainfall		Iced Pavement w/ Rainfall	
TEST NO.	3-3		3-4**		3-5**	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.65	1.27*	1.53	1.70	0.56	1.44
BOSCHUNG	0.80	0.49	2.03	1.34	0.35	0.76
LUFFT	0.53	0.37	1.73	1.43	0.40	1.20
SSI	0.37	0.70	2.47	2.51	0.69	1.40
VAISALA	1.28	2.75	1.50	1.59	2.42	0.63

1. Values in table are Mean Absolute Differences between sensor and baseline temperature in Degrees Celsius
2. Values labeled with an "*" indicate that the difference between the sensor and baseline data is statistically significant
3. Tests labeled with an "**" indicate that there were too few data points to perform a statistical significance test
4. N/A represents test data not available, see test result section for more detailed explanation

Appendix E

Detailed Test Results
(Available Upon Request)